

Determination of the coercive field from the interaction between domain walls and mechanical defects

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In this article, we evaluate the coercive field for electrical steel sheets from the interaction of magnetic domain walls with mechanical defects. The stress distribution is computed for the dislocation lines and the interstitial atoms, modeled as a point force. The orientation of the magnetization in the domain wall with mechanical defect is computed with a finite element method. The coercive field is determined from the variation of the domain wall energy with the relative position of the domain wall and the defect. Finally, the results are homogenized and the macroscopic coercive field is compared with experimental results. The prediction of the coercive field corresponds to the measured one for electrical steel sheets with various grain sizes.

Index Terms—Coercive force, finite element analysis, magnetic domain walls, magnetomechanical effect, micromagnetics.

I. INTRODUCTION

THE coercive field is one of the main driving properties of the hysteresis losses in soft ferromagnetic materials. Most of the hysteresis models require the knowledge of the coercive field [1], [2]. However, the coercive field is always determined experimentally [3] which prevents the prediction of the magnetic hysteresis losses.

The coercive field corresponds to the magnetic field strength to apply for unpinning a domain wall from a defect. Among the various types of mechanical defects in the material, we focus on the dislocation and the interstitial atoms [4]. The former corresponds to an imperfection in the crystal lattice and results in a dislocation line characterized by the Burger vector [5], [6]. The latter corresponds to the placement of a light atom between two atoms of the crystal lattice [7]. The elastic field around a dislocation can be evaluated by imposing a displacement discontinuity in the crystal lattice. In anisotropic media, the calculation of the stress field involves the integration of the Green function by following the method in [5]. The interstitial atoms can be modeled by a point force applied between two atoms of the crystal lattice. The calculation of the stress field around a point force in anisotropic media involves also the integration of the Green function as reported in [8].

The coercive field could be predicted by evaluating the energy involved by the domain wall for crossing a mechanical defect [9], [10]. L. Néel postulates the magnetomechanical energy of the defects. The energy required to cross a defect is evaluated indirectly by considering the stray field energy introduced by the defect in the domain. The coercive field calculated by this method contains two terms, one arise from the mechanical defect and the other one from the chemical impurities. Although the model assumes the form of the magnetomechanical energy due to the defect, the coercive field can be estimated for various alloys [9]. In [10], the magnetic energy of a domain wall is resolved with the Betrami's simplification of the Euler-Lagrange equation, and then the variation of the

stress field due to a dislocation is injected in the differential form of the domain wall equation. The stress field around a dislocation is determined in the case of isotropic material. Although the variation of the stress field within the domain wall is neglected to due the Betrami's simplification, the coercive field is evaluated with the probability to unpin a domain wall with magnetic force produced by a magnetic field. In [11], the interaction of dislocations and the domain wall is computed with a micromagnetic simulation in 2D. The stress field around a dislocation is computed with the Peierls-Nabarro model in the case of an isotropic material. The magnetic field to unpin a defect is evaluated by applying an external field until the domain wall crosses the defect with a Barkhausen jump.

In this paper, we propose to model the coercive field from energy interaction between the Bloch domain wall and the defects. The stress field around the dislocation and the interstitial atoms is considered in the presence of the anisotropy. The magnetization orientation in the domain wall is evaluated by minimization of the energy from a 1D finite element formulation. Finally, the macroscopic coercive field is determined by homogenizing the coercive field for an individual defect. The resulting model is validated against the experiments conducted by Landgraf et al. [3] in case of FeSi alloys with various grain sizes.

II. METHODS

The coercive field h_c can be evaluated with the defect volume fraction v_d by [9]

$$h_c = \frac{v_d}{2\mu_0 M_s} \max \left(\frac{\partial \gamma}{\partial z_d} \right) \quad (1)$$

where μ_0 is the vacuum permeability, M_s is the saturation magnetization, γ is the domain wall energy, and z_d is the relative position between the center of the domain wall and the center of the defect. The domain wall energy γ is computed by integrating the total energy W_t along the direction z , normal

to the plane of the domain $\gamma(z_d) = \int_{-\infty}^{+\infty} W_t(z_d) dz$. The total energy W_t is composed of the exchange energy W_{ex} , the magnetocrystalline anisotropy energy W_{an} and the magneto-elastic energy $W_{\sigma}(z_d)$. Although the domain wall normal is usually aligned along an easy axis, we assume that it can be inclined by an angle α to be colinear with the normal of the dislocation line. The magnetization orientation $\mathbf{m}$ rotates within the Bloch wall by the angle ϕ . It is given by

$$\mathbf{m} = \begin{bmatrix} \cos \phi(z) \\ \cos \alpha \sin \phi(z) \\ \sin \alpha \sin \phi(z) \end{bmatrix} \quad (2)$$

The exchange energy is given with the exchange energy constant A_{ex} by

$$W_{ex} = A_{ex} \left(\frac{\partial \phi}{\partial z} \right)^2 \quad (3)$$

The magnetocrystalline anisotropy energy is given with the first and the second anisotropy constants K_1 and K_2 by

$$W_{an} = K_1 (m_1^2 m_2^2 + m_2^2 m_3^2 + m_3^2 m_1^2) + K_2 m_1^2 m_2^2 m_3^2 \quad (4)$$

The stress field $\sigma(z - z_d)$ around the defect can be defined with a decaying term $F(z - z_d)$ and the tensor $\sigma_0(z_d)$ corresponding to the stress state at the origin of the defect. The magnetoelastic energy is evaluated with the magnetostriction ε_μ

$$W_{\sigma} = -F(z - z_d) \sigma_0(z_d) : \varepsilon_\mu \quad (5)$$

which is defined by

$$\varepsilon_\mu = \frac{3}{2} \begin{bmatrix} \lambda_{100}(m_1^2 - \frac{1}{3}) & \lambda_{111}m_1m_2 & \lambda_{111}m_1m_3 \\ \lambda_{111}m_1m_2 & \lambda_{100}(m_2^2 - \frac{1}{3}) & \lambda_{111}m_2m_3 \\ \lambda_{111}m_1m_3 & \lambda_{111}m_2m_3 & \lambda_{100}(m_3^2 - \frac{1}{3}) \end{bmatrix} \quad (6)$$

The magnetization angle $\phi(z)$ is distributed so as to minimize the domain-wall energy. It consists in solving $\int_{-\infty}^{+\infty} \partial W_t / \partial \phi dz = 0$. By employing the Gateau derivative, the minimization of the energy can be expressed with the test function $\psi(z)$ by

$$2A_{ex} \int \frac{\partial \phi}{\partial z} \frac{\partial \psi}{\partial z} dz = - \int \psi \left[\frac{\partial W_{an}}{\partial \phi} + \frac{\partial W_{\sigma}}{\partial \phi} \right] dz \quad (7)$$

The functions $\phi(z)$ and $\psi(z)$ are expressed with the shape functions $N_n(z)$ and the value ϕ_n and ψ_n at the node z_n . The non-linear terms in the right side of the equation (7) are decomposed into series expansions. The Ritz-Galerkin method is applied so that the term ψ_n vanishes from both sides of the equation. The resulting system of equations is solved iteratively until the norm of the residual is lower than 10^{-12} W/m². In order to enforce the position of the domain wall and avoid the Barkhausen jump, the angle is forced to be $\pi/2$ at $z = 0$. This point is located at the middle of a discretized segment in order to avoid decoupling both side of the domain wall with an equivalent Dirichlet boundary condition. The natural Neumann boundary condition $\partial \phi / \partial z = 0$ is applied at both extremities of the domain wall. The angles are initialized with the solution without the defect, determined analytically.

III. RESULTS AND DISCUSSION

In Fig. 1, the transmission electron microscopic image presents the pinned domain wall in the middle of the dislocation line.



Fig. 1. Transmission electron microscopic image of a domain wall pinned to a dislocation. The domain wall is pinned in the middle of the dislocation line.

In Fig. 2a, the domain wall energy is represented for different positions of the interstitial atom. In Fig. 2b, the predicted coercive field matches with the measured coercive field for various grain sizes d_{grain} of a FeSi alloy [3]. The coercive field term which depends on the chemical impurities remains constant regardless of the grain size. The model evaluates this term to 27 A/m and the experimental value is evaluated to 26.4 A/m by fitting the expression $h_c = h_{dc} + I/d_{\text{grain}}$ to the measurement.

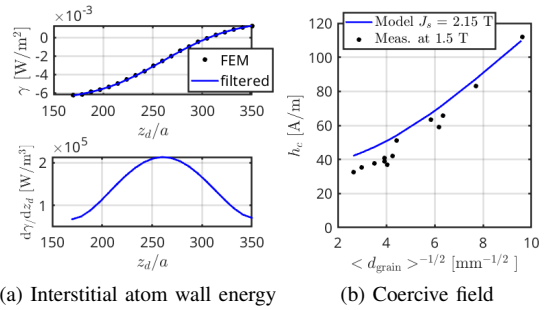


Fig. 2. Domain wall energy with the distance to the center of interstitial atom, a is the crystal lattice distance and comparison of the predicted coercive field and the measured coercive field in FeSi alloys [3]

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