Coercivity in Soft Magnetic Material under Alternative Mechanical Stress

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The mechanisms leading to coercivity reduction under dynamic mechanical stress obtained on soft ferromagnetic samples are modelled. The coercive forces related to magnetoelastic anisotropy fluctuations are investigated in polycrystalline magnetic materials to quantify the effects of applied dynamical mechanical stress. Domain Wall displacement is so reconsidered and mechanism allowing magnetization reversal in magnetoelastic defects is explained. Therefore, energy barriers that pin DW at the mesoscopic scale of the magnetoelastic defects are analytically calculated and the cooperative behaviour between magnetoelastic defects due to magnetostatic energy is emphasized. Finally, the coercive field decrease is estimated and compared to measurements on $Fe_{49}Co_{49}V_2$ material.

***Index Terms*—coercive force, Iron alloys, magnetoelasticity, magnetostatics, stress.**

I. Introduction - Magnetoelastic anisotropy fluctuations in magneto-elastic defects

The effect on the hysteresis of a repeated application of mechanical stress is described experimentally for ferromagnetic materials since more than half a century [1]. However, the mechanisms of significant reduction of coercivity observed for these solicitations are very fewly explicited. Indeed, the models developed to quantify the interactions between magneto-elastic behavior and coercivity are often restricted to static mechanical stress [3]. To explain the experimental results on $Fe_{49}Co_{49}V_2$ subjected to coercivity reduction under dynamic mechanical stress [2], these models should be extended. To understand these interactions, the historical Neel model [4] is our starting point. This model considers the deviations of the magnetization direction inside domains due to local changes in direction of easy magnetization, as a source of coercivity. Indeed, any deviation of the magnetization implies the emergence of magnetic charges which are then diluted in domains. The magnetostatic energy that results will then vary close to a Bloch Domain Wall (DW) - i.e when DW intersects the positive and negative charges. This energy thus fluctuates and, depending on the DW position, contributes to explain the coercivity.

In addition to the metallurgical defects such as cavities and non-magnetic inclusions which induce a discontinuity of the magnetization and thus the appearance of magnetic charges, other defects should be considered. The magnetoelastic anisotropy fluctuations due to irregularly distributed residual stresses also lead to a deviation of the magnetization. In this study, these defects called magneto-elastic defects (denoted *md*) will be considered as an important source of coercivity, and will be modelled. These residual stresses can be due to dislocations, grain boundaries and defects arrangement. These defects are characterized by the establishment of an elastic stress field that attenuates around them [5]. These residual stresses are also due to strain incompatibilities between grains and stresses of magnetostrictive source that are resulting [6]. For these defects, the characteristic size of the elastic stress field is estimated between few 10 nm, i.e larger than the DW size, and less than the domain size (few micrometers [7]) and thus less than the grains size (≈ 10 μm [8]) for $Fe_{49}Co_{49}V_2$ alloys. Thus, the model is established at the intermediate scale between DW and domain size.

Any defects, characterized by a fluctuation of the magnetoelastic anisotropy under the effect of residual stresses, that induce a deviation of the magnetization inside the domains, are described similarly. The different anisotropy energies: magneto-crystalline, magneto-elastic and magnetostatic which depends on the DW position, are evaluated for a defect and then used to deduce the energy and the direction of magnetization at equilibrium depending of the DW position relative to the defect. The coercive forces that are pinning the DW on a defect (Fig. 1-a-b) will be deduced. Furthermore, to the magnetoelastic anisotropy term due to residual stress is added the applied external stress. The established model allows to understand the mechanisms that lead to reduction of coercivity when applying an external mechanical stress.

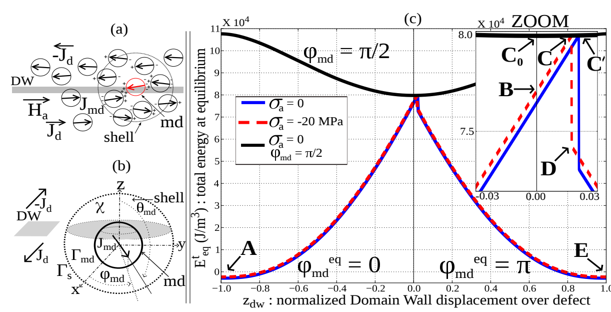

Fig. 1. (a): Representation of DW displacement in a cluster of MDs by polarization reversal inside a MD. (b): Magnetoelastic Defect surrounded by magnetic shell. (c) Equilibrium energy density of MD: polarization direction imposed along Oy (dotted line): with residual stress $\sigma_i = 100$MPa along Ox without external stress (solid line) and with external stress $\sigma_a = -20$MPa along Ox (dashed line).

II. Analytical model

Fields of irregularly distributed residual stresses are considered via magnetoelastic anisotropy, through defects representation. These are characterized by the deviation of their magnetization relative to the domain magnetization direction. Thus, the balance between the different energies: magneto-elastic, magneto-crystalline, Zeeman and magnetostatic are considered. In [4], besides a distribution function that associates a characteristic length fluctuations of the magneto-elastic anisotropy, the difficult issue of magnetostatics is processed. Indeed, at the cost of excessively heavy analytical developments, magnetostatic interactions between defects are considered. Consequently, and in accordance with the saturation approach law in [4], cooperative behavior between defects, which favors magnetization deviations, is established.

To avoid too heavy mathematical developments, another way is searched to describe the cooperative behavior between defects. The starting point relies on the calculation of the magnetostatic energy of a magnetic field in a direction different from the surrounding environment, i.e the domain magnetization direction. In [9], calculation of the magnetostatic energy for a non-magnetic inclusion intersected by a DW is detailed. This calculation can be extended to the situation of a sphere magnetized in a different direction from adjacent domains. The difficulty then concerns the magnetostatic energy amplitude that remains much higher than the other anisotropy energy terms. The magnetization deviations induced by residual stresses are then almost prohibited. If the interactions between nearby defects are not modelled, then the magnetostatic energy is overrated. The description of the environment that surrounds the defect - a uniform magnetization - has to be reconsidered. To account for the cooperative behavior between defects that promotes the screening of magnetostatics, a core-shell description is selected. This shell models nearest defects in the manner of a spherical shield which attenuates fields and reduces the strength of the magnetostatic energy.

Subsequently, the defects will be considered spherical, characterized by a uniform magnetization J_{md} oriented along the unit vector $\overrightarrow{u_{md}}$ and identified in spherical coordinates. These defects are subjected to a residual stress described by a constant amplitude σ_i and a random direction along $\overrightarrow{u_i}$. Domains are themselves magnetized in the direction Ox and the position of the thin DW is described by the coordinate z_{dw}. The shell that covers nearby defects is described by the constitutive law $\overrightarrow{B_s} = \mu_0 \overrightarrow{H_s} + \overrightarrow{\delta J_d} + \overrightarrow{J_d} = \mu_0 (\chi+1) \overrightarrow{H_s} + \overrightarrow{J_d}$ where the indices s and d relate to the shell and the domain respectively.

The solutions of scalar potential U_{md} from the Laplace equation are the spherical harmonics. The densities of magnetic charges that appear at the interfaces defect/shell and shell/domain are also developed following spherical harmonics, as:

$$\begin{aligned}\varepsilon \overrightarrow{u_{md}} \cdot \overrightarrow{u_r} = \sum_{m=-1}^{1} \sum_{n=0}^{\infty} (-m \left(\frac{g}{4\pi}\right)^{1/2} \pi e^{i\varphi_d} (2Q_n(z_{dw}) \\ + 2(\text{if } n=0))) Y_n^{(m)}(\varphi, \theta)\end{aligned} \quad (1)$$

where $\varepsilon = 1$ if $z < z_{dw} = cos(\theta_{dw})$ or -1 else, and:

$$\left(1-z^2\right)^{1/2} P_n^{(1)}(z) = \frac{n(n+1)}{(2n+1)} \mathrm{d}Q_n = g \cdot \mathrm{d}Q_n \quad (2)$$

where $P_n^{(1)}$ are the Legendre polynomials. The boundary conditions finally allow to specify the form of the potential solution. The magnetostatic energy E_{ms} on a default is finally calculated according to:

$$E_{ms}(z) = \frac{1}{2} \int_{\Gamma_{md}} U_{md}|_{R_{md}} \left(\overrightarrow{J_{md}} \cdot \overrightarrow{u_r}\right) \mathrm{d}\Gamma_{md} \quad (3)$$

III. Discussions

The total energy E_t associated with a defect intersected by a DW, is the sum of the magnetostatic energy as function of z_{dw} follows (3), magneto-crystalline and magneto-elastic described by uniaxial anisotropy along directions Ox and $\overrightarrow{u_i}$ respectively. For a position z_{dw} of the DW, the MD magnetization direction at equilibrium $\varphi_{md}^{eq}(z_{dw})$ is determined. The total energy E_t^{eq} is then plotted as function of z_{dw} in Fig. 1-c.

The pinning field of the DW on a defect is expressed as follows: $H_r = \frac{1}{2J_d} \frac{\partial}{\partial z_{dw}} E_t^{eq}(\varphi_{md}^{eq}(z_{dw}))$. For a planar DW, the coercive force is derived by averaging process over all the defects that intersect the wall and for all positions of the wall as $H_c = \overline{\langle\langle H_r \rangle\rangle}$ [10]. To discriminate defects which contribute to the coercivity, only two situations are studied following the direction of the residual stress, along Ox or Oy (the product $\lambda\sigma_i$ is positive). For a residual stress defect along Oy, the intermediate magnetization direction Oy is an easy magnetization direction and the deducted profile of established expressions is symmetrical. By averaging effect, the coercive field associated with these defects is zero. At the opposite, for a residual stress defect along Ox, the magnetization is maintained parallel to the domain while the energy is below the threshold corresponding to the energy of a defect in the intermediate magnetic direction Oy. This results in an asymmetry (CD in Fig. 1-c), which means coercivity, because the threshold is only crossed when $z_{dw} > 0$. The gap between the energy related to these defects for $z_{dw} = 0$ and this threshold, is deduced from the energy supplied to the defect in order to make the profile symmetrical and reduce the pinning field. This difference is very small when the DW exceeds the middle of the defect, but nearby defects are themselves exceeded for more than half in the opposite direction. Magnetostatic which exerts pressure in order to reverse the defect magnetization, it is the effect of the above cooperative behavior.

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