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Multiscale modeling of a low magnetostrictive Fe-27wt%Co-0.5wt%Cr alloy

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The present paper deals with the improvement of a multi-scale approach describing the magneto-mechanical coupling of Fe-27wt%Co-0.5wt%Cr alloy. The magnetostriction behavior is demonstrated as very different (low magnetostriction vs. high magnetostriction) when this material is submitted to two different final annealing conditions after cold rolling. The numerical data obtained from a multi-scale approach are in accordance with experimental data corresponding to the high magnetostriction level material. A bi-domain structure hypothesis is employed to explain the low magnetostriction behavior, in accordance with the effect of an applied tensile stress. A modification of the multiscale approach is proposed to match this result. © 2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). <https://doi.org/10.1063/1.5007755>

I. INTRODUCTION

For several years, an increase of the electrical power is researched in the aeronautical field leading to an increasing number of electrical devices on board. This development shall not be accompanied by an increase in weight. One solution is the use of higher power density magnetic materials. A good candidate for power transformers is the Fe-27wt%Co-0.5wt%Cr alloy exhibiting the highest saturation magnetization compared to the other magnetic materials. Unfortunately, this material leads to high level of noise emission due to its strong intrinsic magnetostriction. Magnetostriction tests performed on strip samples have shown that annealing conditions after cold rolling induce a variation of the magnetostrictive behavior.¹ Indeed, an annealing in the austenitic phase (γ phase) (material called $FeCo_A$) induces a strong magnetostriction from low levels of induction (figure 1). An annealing in ferritic domain (α phase) (material called $FeCo_B$) brings on the contrary to a low magnetostriction over a wide induction range ($\pm 1,5T$) (figure 1). These very different behaviors are obtained while crystallographic texture and grain size are strictly the same for both materials.¹ The assumption of a selection of magnetic bi-domains (magnetic domains separated by 180° domain wall) within the rolling plane has been emitted to explain the behavior of $FeCo_B$. A modeling attempt is proposed in this paper using the so-called multiscale magnetomechanical model.² This modeling is complemented by new experimental results confirming the magnetic bi-domain configuration in $FeCo_B$.

II. MATERIAL, EXPERIMENTAL PROTOCOL AND RESULTS

The alloy studied here (Fe-27wt%Co-0.5wt%Cr alloy) is a ferromagnetic material which presents the highest saturation magnetization ($M_s = 2.38T$) of all commercial soft magnetic alloys,

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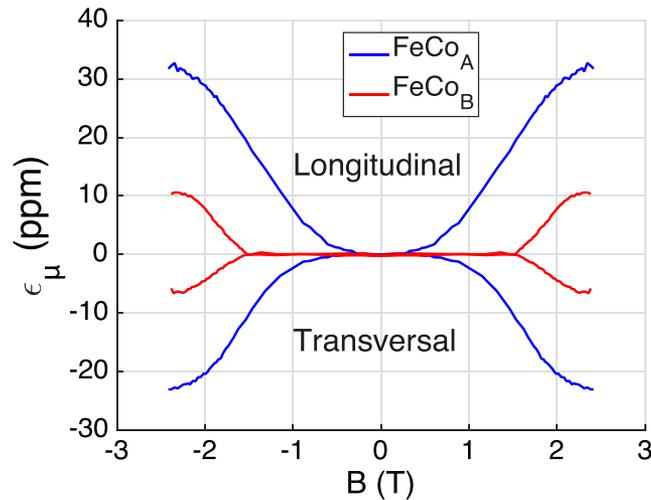


FIG. 1. Magnetostrictive behavior of Fe-27wt%Co-0.5wt%Cr alloy annealed in the austenitic phase ($FeCo_A$) and in the ferritic phase ($FeCo_B$).

a high magnetocrystalline anisotropy constant ($K_1 = 38 \text{ kJ/m}^3$) and magnetostriction constants $\lambda_{100} = 50\text{-}60$ ppm and $\lambda_{111} = 0$ to -5 ppm in the ordered state (data from Hall³). The material is a commercial based alloy AFK1 from APERAM, supplied at different states of the thermomechanical process from the hot rolled state. Samples (140 mm of length, 12.5 mm of width and 0.22 mm of thickness) that have been annealed in the austenitic domain (1000°C) after a severe cold rolling (70%) and slowly cooled (300°C/h) are denoted $FeCo_A$. Samples annealed in the ferritic domain (900°C) are denoted $FeCo_B$. The anhysteretic magnetostrictive behavior has been characterized at the room temperature.⁴ Strain gauges stuck on each face of strip samples allow the magnetostriction along the direction of the applied magnetic field and transversally of the applied magnetic field (denoted Longitudinal and Transversal magnetostriction respectively) to be characterized. Results reported in figure 1 show that $FeCo_B$ exhibits a quasi-null magnetostriction over a wide range of induction ($\pm 1.5\text{T}$) very different from the $FeCo_A$ behavior.

Magnetostriction tests under uniaxial tensile stress have been performed next on sample $FeCo_A$ following an experimental procedure detailed in Ref. 4 (stress is applied in the magnetic field direction). An anhysteretic magnetostriction measurement is performed at different stress levels. Results reported in figure 2 show a progressive shift of the magnetostriction at zero magnetization (so-called ΔE effect⁵) and a reduction of magnetostriction amplitude with applied stress. Indeed, the application of a tensile stress to a positive magnetostriction material increases the volume fraction of magnetic

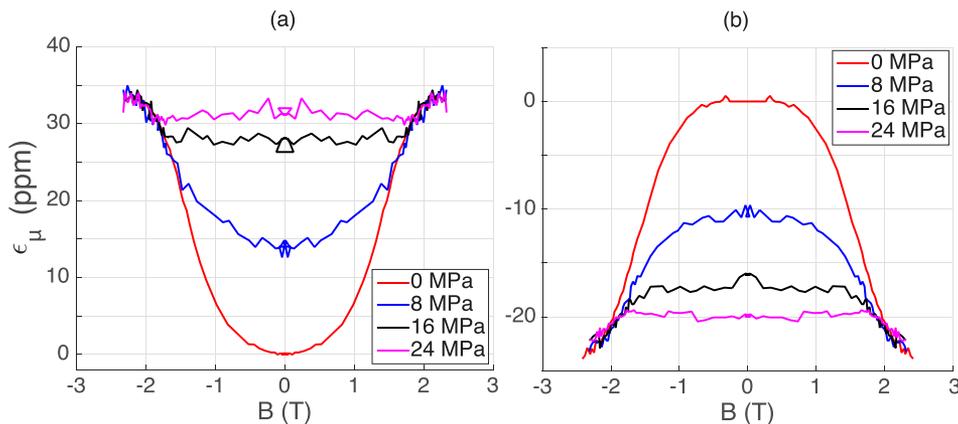


FIG. 2. Magnetostrictive behavior of $FeCo_A$ submitted to tensile loading (a) longitudinal; (b) transversal - experiments.

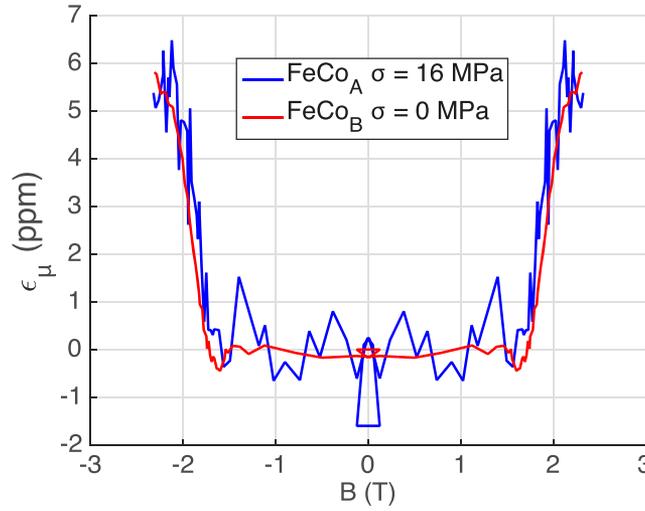


FIG. 3. Comparison of the magnetostrictive behavior between $FeCo_B$ (stress-free) and $FeCo_A$ ($\sigma = 16\text{MPa}$).

domains oriented nearby to the direction of the applied stress,⁶ leading to a bi-domain structure. The magnetization process consequently proceeds with a dominant 180° domain wall displacement mechanism in a wider induction range. As illustrated in figure 3, the $FeCo_A$ sample submitted to a 16 MPa uniaxial tensile stress exhibits a magnetostriction behavior very close to $FeCo_B$ in stress-free condition. This result is in accordance with the bi-domain configuration hypothesis retained to explain the behavior of $FeCo_B$ material.¹ The modeling of such behaviors constitutes an important next step.

III. MULTISCALE MODELING AND RESULTS

The proposed multiscale model is relevant for the magneto-mechanical behavior of soft magnetic materials. It derives from the previous works of Daniel.² The first scale is the domain scale, where magnetic quantities can be considered homogeneous. The second scale is the grain scale considered as an assembly of domain families. Just above, is the polycrystalline scale considered as an assembly of grains and usually denoting the representative volume element (RVE). Our objective is to calculate the macroscopic magnetostriction tensor ϵ_μ as function of the macroscopic applied field \vec{H} and applied stress σ for both materials.

A. Multiscale modeling of the $FeCo_A$ material

In a magnetic domain family α , the magnetization vector is defined as $\vec{M}_\alpha = M_s \vec{\gamma}$ where $\vec{\gamma}$ is the direction of the magnetization vector. The exchange energy inside a domain is zero due to no spatial variation of the magnetization. The free energy of a domain family is given by (eq. 1).

$$W_{tot}^\alpha = W_K^\alpha + W_Z^\alpha + W_\sigma^\alpha \quad (1)$$

The magnetocrystalline anisotropy energy in case of cubic anisotropy is given by eq. 2 where γ_i indicate the direction cosines of $\vec{\gamma}$. This energy tends to align the magnetization along the easy axes (crystallographic axes $\langle 100 \rangle$ in case of cubic symmetry and positive magnetocrystalline constant K_1). 6 domains families are considered for $FeCo_A$ associated with the 6 easy axes.

$$W_K^\alpha(cub) = K_1(\gamma_1^2\gamma_2^2 + \gamma_2^2\gamma_3^2 + \gamma_3^2\gamma_1^2) + K_2(\gamma_1^2\gamma_2^2\gamma_3^2) \quad (2)$$

W_Z^α indicates the Zeeman (magnetostatic) energy (eq. 3). The first term tends to align the magnetization along the direction of the local magnetic field \vec{H}^α , defined as function of the applied magnetic field (at the domain scale) \vec{H}_0^α and the demagnetizing field \vec{H}_d^α . The demagnetizing field is on the other hand connected to the magnetization generated by the body itself and to the form-effect second-order tensor N (eq. 4). ζ parameter reflects the effect of surrounding medium and fix the maximum amplitude of the demagnetizing effect. The magnetic field is considered homogeneous over the grain and

over the volume ($\vec{H}_0^\alpha = \vec{H}$). Only a macroscopic demagnetizing term (surface effect) is considered for calculations (ζ and N are homogeneous over the volume).

$$W_Z^\alpha = -\mu_0 \vec{M}^\alpha \cdot \vec{H}^\alpha = -\mu_0 \vec{M}^\alpha \cdot \vec{H}_0^\alpha - \mu_0 \vec{M}^\alpha \cdot \vec{H}_d^\alpha \quad (3)$$

with

$$\vec{H}_d^\alpha = -\zeta N \vec{M}^\alpha \quad (4)$$

W_σ^α refers to the magneto-elastic energy (eq. 5) linked to the interaction between magnetization and elastic deformations of the crystal lattice. ϵ_μ^α is the magnetostriction strain second-order tensor which can be described with two parameters in the case of cubic crystallographic symmetry considering an isovolume deformation (eq. 6 - written in the crystallographic frame - CF). λ_{100} and λ_{111} respectively denote the magnetostrictive constants corresponding to the magnetostriction strain measured along directions $\langle 100 \rangle$ and $\langle 111 \rangle$ axes of a single crystal when it is magnetized at saturation along these directions. σ^g is the second-order stress tensor defined at the upper scale (i.e. grain scale g). This formulation derives from a homogeneous deformation hypothesis at the grain scale. For simplicity's sake, a homogeneous stress hypothesis is employed from the grain to macroscale ($\sigma^g = \sigma$) for both materials.

$$W_\sigma^\alpha = -\sigma^g : \epsilon_\mu^\alpha \quad (5)$$

$$\epsilon_\mu^\alpha = \frac{3}{2} \begin{pmatrix} \lambda_{100}(\gamma_1^2 - \frac{1}{3}) & \lambda_{111}\gamma_1\gamma_2 & \lambda_{111}\gamma_1\gamma_3 \\ \lambda_{111}\gamma_1\gamma_2 & \lambda_{100}(\gamma_2^2 - \frac{1}{3}) & \lambda_{111}\gamma_2\gamma_3 \\ \lambda_{111}\gamma_1\gamma_3 & \lambda_{111}\gamma_2\gamma_3 & \lambda_{100}(\gamma_3^2 - \frac{1}{3}) \end{pmatrix}_{CF} \quad (6)$$

The magnetization direction at the domain scale α (defined by spherical angles θ_α and ϕ_α) is calculated after a minimization of the free energy (eq. 7).

$$W_{tot}^\alpha(\theta_\alpha, \phi_\alpha) = \min(W_{tot}^\alpha) \quad (7)$$

The single crystal g is composed by the 6 domain families α . The elastic stiffness and magnetic susceptibility are considered homogeneous over the grain. The magnetostriction strain and the magnetization at the grain scale (ϵ_μ^g and \vec{M}^g) are consequently defined thanks to simple average operations (eq. 8). f_α indicates the volume fraction of a domain family α . It is calculated using a probabilistic Boltzmann function (eq. 9) where A_s is an adjusting parameter related to the initial magnetic susceptibility.

$$\epsilon_\mu^g = \langle \epsilon_\mu^\alpha \rangle = \sum_\alpha f_\alpha \epsilon_\mu^\alpha \quad \vec{M}^g = \langle \vec{M}^\alpha \rangle = \sum_\alpha f_\alpha \vec{M}^\alpha \quad (8)$$

$$f_\alpha = \frac{\exp(-A_s W_{tot}^\alpha)}{\sum_\alpha \exp(-A_s W_{tot}^\alpha)} \quad (9)$$

A set of 440 representative orientations (extracted from EBSD analysis) is used to define the polycrystalline scale for both $FeCo_A$ and $FeCo_B$. The macroscopic magnetization and magnetostriction are calculated by simple averaging over the orientation data file (eq. 10).

$$\vec{M} = \langle \vec{M}^g \rangle \quad \epsilon_\mu = \langle \epsilon_\mu^g \rangle \quad (10)$$

B. Multiscale modeling of the FeCo_B material

The modeling of $FeCo_B$ material uses the same rules than for $FeCo_A$. Only the definition of magnetocrystalline energy differs since the assumption of bi-domain configuration is not in accordance with the previous definition of anisotropy. A uniaxial definition of anisotropy is required. Moreover the macroscopic demagnetizing surface effect that was acting during the initial magnetic domain distribution led to a selection of the bi-domains preferentially oriented in the rolling plane. Eq. 11 gives the new definition of the magnetocrystalline anisotropy where γ_u refers to the direction cosine of the magnetization vector with respect to the $\langle 100 \rangle$ axis the closest to the sheet plane, allowing the number of domain families to be changed from 6 to 2. Meanwhile, it is possible that a minor

TABLE I. Physical constants used for the multiscale modeling.

$M_s(A/m)$	$K_i(kJ/m^3)$	N	ζ	λ_i (ppm)
1.89×10^6	$K_1=38$ $K_2=0$ $K_u=8$	$N_{xx} = 0$ $N_{yy} = 0$ $N_{zz} = 1$	1.1×10^{-4}	$\lambda_{100} = 60$ $\lambda_{111} = -0.5$

part of the grains does not follow this rule, where the $\langle 100 \rangle$ chosen axis is random. The numerical simulations proposed below consider 20% of random orientations.

$$W_K^\alpha(uni) = K_u(1 - \gamma_u^2) \quad (11)$$

C. Modeling results

The physical constants used for the multi-scale modeling are gathered in Table I. Adjusting constant $A_s = 3 \times 10^{-3} \text{ m}^3/\text{J}$ is chosen for both materials. Numerical results can be compared to experimental measurements, for both materials, with or without applied stress, and considering longitudinal or transversal magnetostriction.

Figure 4 gives a first sight of the ability of the model for the prediction of magnetostriction of $FeCo_A$ material. Longitudinal and transversal magnetostriction are properly modeled. This result shows on the other hand that the approach that considers an equiproportion of the 6 domain families is unable to model the $FeCo_B$ material behavior. The addition of an external mechanical loading along the applied magnetic field in the multi-scale model induces a modification of the local magnetic state as illustrated in figure 5. Thus, magnetic domains oriented toward the mechanical loading direction are favored. The magnetostriction of $FeCo_A$ submitted to a 16 MPa tensile stress is lower than stress free $FeCo_A$ and results are in a very interesting accordance with experimental results (figure 2).

Figure 6 allows the experimental data of $FeCo_B$ to be compared with the model considering a magnetic bi-domain structure. The distribution of magnetic domains within the rolling plane induces no deformation up to 1.5 T due to a dominance of 180° domain wall displacements during the magnetization. Beyond this induction level, magnetostriction occurs by magnetization rotation. This numerical result shows that a bi-domain selection hypothesis implemented by an in-plane uniaxial anisotropy seems to be the dominant mechanism that occurs in the $FeCo$ material annealed in the ferritic phase.

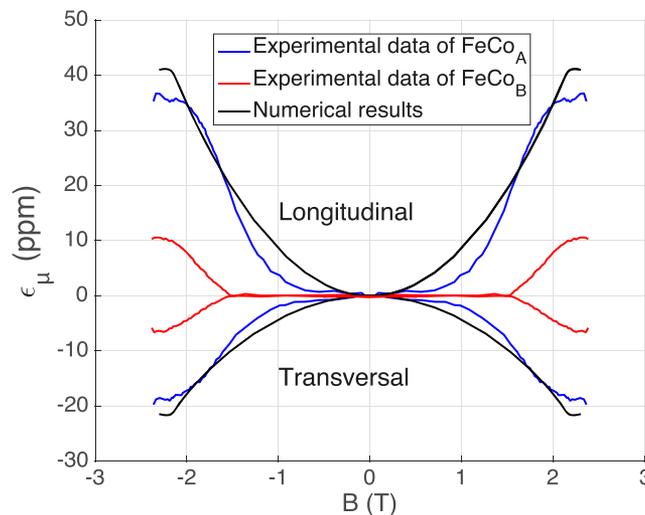


FIG. 4. Comparison of the magnetostrictive behavior obtained from experimental results and numerical data.

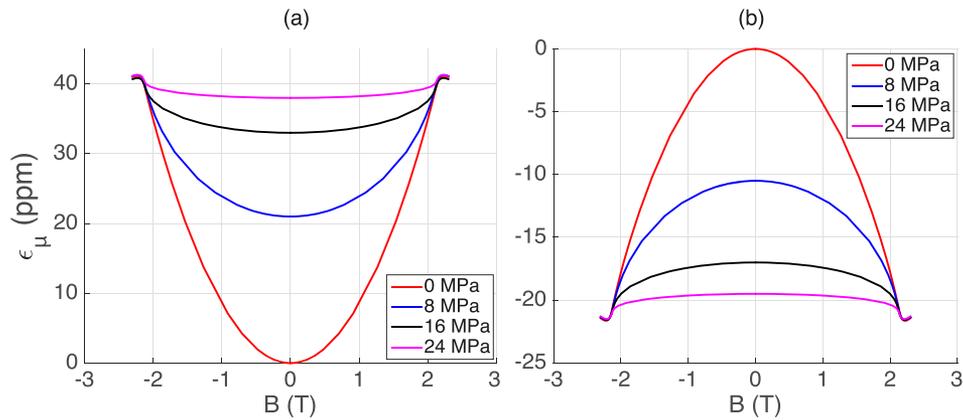


FIG. 5. Magnetostrictive behavior of $FeCo_A$ submitted to tensile loading (a) longitudinal; (b) transversal - modeling.

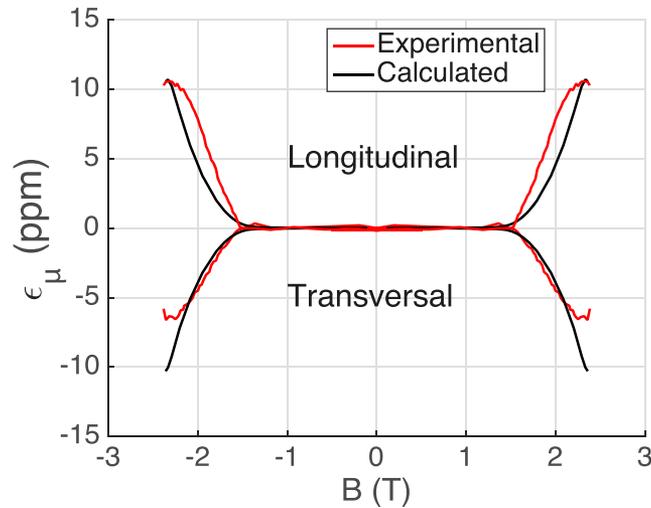


FIG. 6. Comparison of the magnetostrictive behavior obtained from experimental results and numerical data considering a magnetic bi-domains.

IV. CONCLUSION

A low and isotropic magnetostriction has been observed for Fe-27wt%Co-0.5wt%Cr strip samples annealed in the ferritic phase. Magnetostriction tests under uniaxial stress have confirmed the hypothesis of a bi-domains structure (domain separated by 180° domain wall) oriented within the rolling plane since a more classical high magnetostriction Fe-27wt%Co-0.5wt%Cr alloy can be transformed into a low magnetostriction Fe-27wt%Co-0.5wt%Cr by this mechanical process. A multi-scale model has been employed for modeling both material including the tensile stress effect. Materials only differ by the definition of the magnetocrystalline energy. The uniaxial formulation allows the bi-domain distribution of the magnetization directions mostly oriented in the rolling plane to be defined, leading to a magnetostrictive behavior similar to experimental results. Other modeling approaches including hysteresis like in Ref. 7 would be able to model this behavior as well by considering the same uniaxial anisotropy.

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