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Effect of plastic straining on magnetostriction of ferromagnetic polycrystals—experiments and multiscale modeling

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Abstract

The influence of plastic deformations on magnetostriction of NO–3% Si–Fe alloy is studied. Experimental measurements are presented. The magnetostriction is strongly anisotropic before deformation and plastic strain tends to homogenize this behavior. The modeling consists in the calculation of a specific residual stresses field and its introduction in the magnetic model. Experiments and modeling are in good agreement.

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Keywords: Magnetostriction; Plastic strains; Multiscale modeling

1. Introduction

The influence of plastic deformations on magnetic behavior has been studied intensively in past years [1]. It is characterized by a strong degradation of magnetic behavior especially for weak plastic strain levels [2] and associated to intergranular stresses [3]. A model was recently proposed to describe the influence of plastic strain on the magneto-mechanical behavior of ferromagnetic materials and experiments showed the ability of this model to predict the degradation of magnetization behavior [4]. On the other hand the magnetostriction measurement is often proposed as a suitable indicator of mechanical state [5], but few experimental results of the influence of plastic strain on magnetostriction are available since Cullity in 1972 [6]. The first objective of this paper is to carry out magnetostriction measurements of plastic strained samples. The second objective is to evaluate the ability of the model to predict these experimental results.

2. Experimental procedure

NO 3% silicon–iron (0.5 mm thick) laminations have been used. Mechanical and magnetic experiments have been performed on 250 mm length and 12.5 mm width specimens cut by electroerosion along the rolling and transverse directions (RD and TD). Uniaxial tensile tests have been carried out at room temperature and constant strain rate $\dot{\varepsilon} = 1 \times 10^{-4}\,s^{-1}$. Strain measurement were performed by strain gauges. Five plastic strain levels have been reached. Anhysteretic measurements of magnetization and magnetostriction have been carried out for increasing plastic strain levels at unloaded state. Description of employed device and measurement procedures can be found in Ref. [7]. Magnetostriction has been measured along both longitudinal and transverse direction of tensile strained specimen. The so-called form effect has been numerically removed[1] [8].

3. Experimental results

Despite a very low plastic strain levels (Table 1), the plastic deformation is homogeneous over the specimens.

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[1]Measured deformation = magnetostriction + form effect.

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Table 1
Plastic strain levels ε_p per direction

ε_p - RD (%)	0.003	0.005	0.021	0.090	0.160
ε_p - TD (%)	0.002	0.004	0.017	0.075	0.145

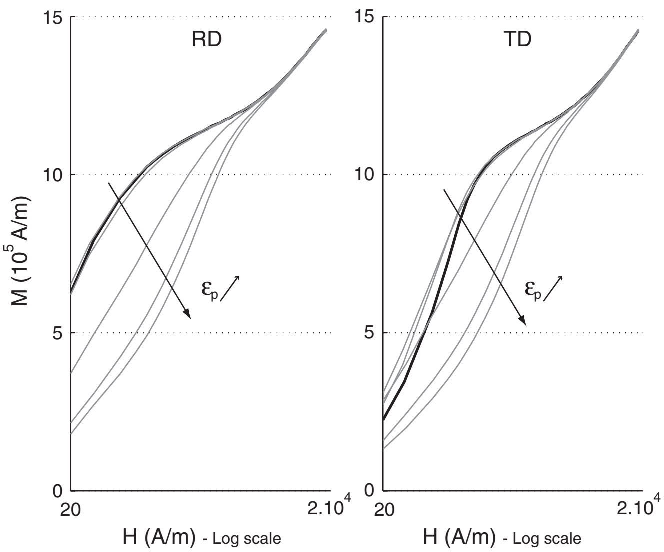

Fig. 1. Anhysteretic magnetic behavior.

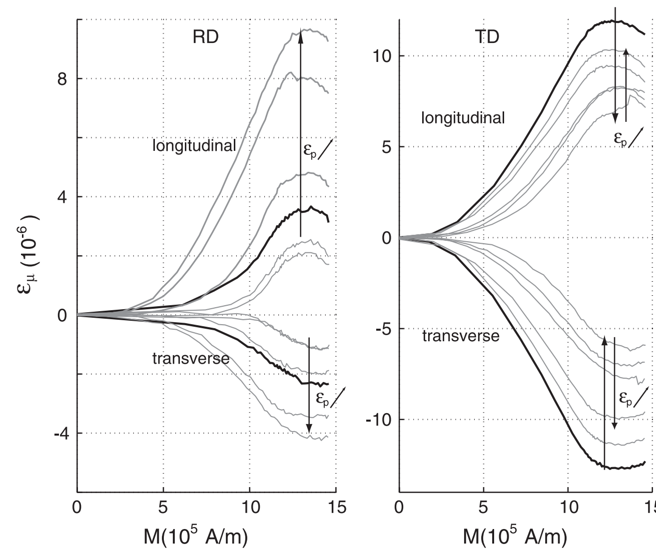

Fig. 2. Anhysteretic magnetostrictive behavior.

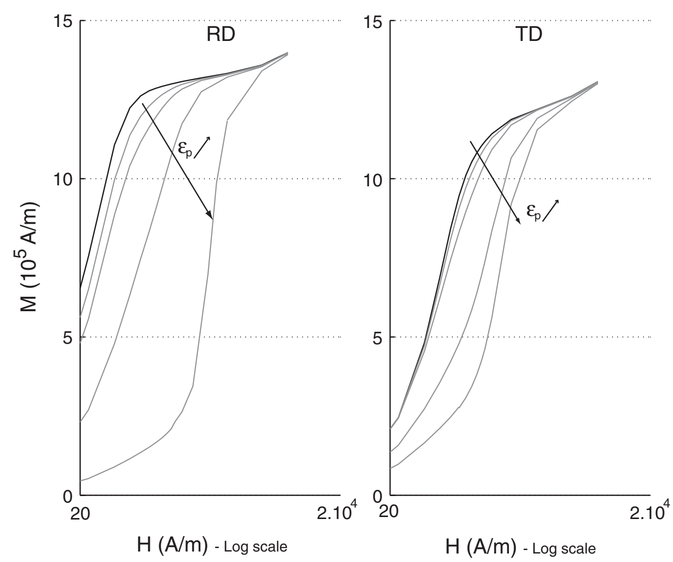

Fig. 3. Multiscale model: magnetization behavior.

Two first straining levels are below the macroscopic yield stress Σ_e: they are referred to as "microplasticity". Three higher levels correspond to usual plasticity. Fig. 1 shows the variations of magnetization behavior as function of strain level for RD and TD (thick lines: unstrained). The increasing strain levels roughly lead to a nonlinear degradation of the anhysteretic behavior as foreseen. This is especially sensitive for the weak and medium magnetic field strength, where maximal decreasing reaches 60%! We note that the two first plastic strain levels lead to a first weak improvement of the magnetization behavior especially along TD for $H < 100\,\mathrm{A/m}$. Fig. 2 shows the experimental results obtained for magnetostriction. Several points are remarkable: the initial behavior is strongly anisotropic (e.g. $\varepsilon_\mu^{\max}(\mathrm{RD-long.}) = 3.5 \times 10^{-6}$ and $\varepsilon_\mu^{\max}(\mathrm{TD-long.}) = 12 \times 10^{-6}$); at low levels, plastic straining has an opposite effect on RD and TD behaviors: magnetostriction amplitude increases for RD and decreases for TD. A global homogenization of the magnetostriction behavior occurs as major consequence; higher plastic strain level leads to progressively the same change for RD and TD. Amplitudes are increasing so that magnetostrictive behavior along TD before and after plastic straining is roughly equivalent (for investigated levels).

4. Micromechanical model of plasticity and multiscale modeling

The modeling procedure is divided in calculation of local stress field first, and multiscale (domain, grain, polycrystal) magnetic modeling, second. Magnetization and magnetostriction behaviors are finally calculated. Ref. [4] explains in detail how the local plastic straining is calculated using microplasticity tools. An orientation data file obtained by EBSD measurement and containing 396 orientations has been used. The multiscale magnetic modeling has been presented in detail elsewhere [9]. It is based on an energetic approach for the equilibrium state of a magnetic domain. Each grain is supposed be divided into domain families associated to "easy" directions. Localization procedures are first required in order to get the local loading at this scale. The volumetric fraction and magnetization of each family are evaluated thanks to a microscopic model. Averaging operations finally allow one to get the mean magnetization and magnetostriction strain across the grains and at macroscale. Fig. 3 plots the modelled magnetization behavior for RD and TD. Initial anisotropy

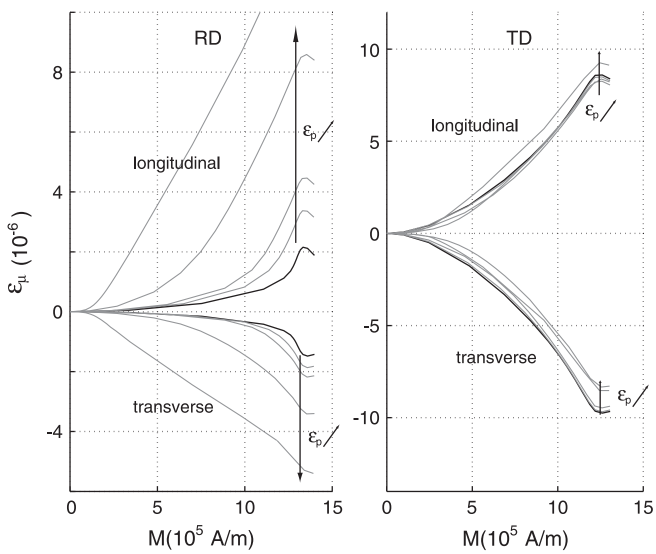

Fig. 4. Multiscale model: magnetostrictive behavior.

and drastic degradation due to plasticity are well described. The rate of degradation is nevertheless different from experiments at various strain levels. Fig. 4 plots the modeled longitudinal and transverse magnetostriction behavior for RD and TD. Initial anisotropy is well fitted even if amplitudes are lower. Influence of plastic straining is in good agreement with experimental results for RD. Initial and final TD behaviors are in accordance with experiments, but the decrease of amplitude at very low straining level is not modeled for TD.

5. Discussion and conclusion

Initial anisotropy was already discussed in a previous paper [7]. It is linked to low anisotropic crystallographic texture associated to initial configuration of domains mainly distributed along RD (same effect occurs for grain-oriented materials). This initial distribution is predicted by the model. The local stress tensor associated to the plastic strain completely destroys this weak configuration and two consequences are the degradation of magnetization behavior in the direction of the tensile test and the homogenization of magnetostriction. Finally higher plastic strain levels lead to an increase of amplitude of magnetostriction. This is in accordance with Cullity's and more recent Makar's observations [6,10], and associated with a major compressive effect along the straining direction.

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