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Two phase modeling of the influence of plastic strain on the magnetic and magnetostrictive behaviors of ferromagnetic materials

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ABSTRACT

A growing interest of automotive industry in the use of high performance steels is observed. These materials are obtained thanks to complex manufacturing processes whose parameters fluctuations lead to strong variations of microstructure and mechanical properties. The on-line magnetic non-destructive monitoring is a relevant response to this problem but it requires fast models sensitive to different parameters of the forming process. The plastic deformation is one of these important parameters. Indeed, ferromagnetic materials are known to be sensitive to stress application and especially to plastic strains. In this paper, a macroscopic approach using the kinematic hardening is proposed to model this behavior, considering a plastic strained material as a two phase system. Relationship between kinematic hardening and residual stress is defined in this framework. Since stress fields are multiaxial, an uniaxial equivalent stress is calculated and introduced inside the so-called magneto-mechanical multidomain modeling to represent the effect of plastic strain. The modeling approach is complemented by many experiments involving magnetic and magnetostrictive measurements. They are carried out with or without applied stress, using a dual-phase steel deformed at different levels. The main interest of this material is that the mechanically hard phase, soft phase and the kinematic hardening can be clearly identified thanks to simple experiments. It is shown how this model can be extended to single phase materials.

1. Introduction

Since the early works of Mateucci and Villari, mechanical stress has been known to significantly change the magnetic behavior of materials (see for instance the works reported in [1]) as well as their magnetostrictive behavior [2]. Many other works have shown that macroscopic magnetic behavior is sensitive to any mechanical loading depending on the loading level (elastic, plastic), the loading sign (tension, compression), and the loading nature (static or dynamic, uniaxial or multiaxial stress). The correlation between mechanical, metallurgical and magnetic states has received increasing attention these last years due to the new ability and requirement to perform magnetic non-destructive monitoring (NDM) of materials and structures [3–5]. Steel manufacturers, for example, plan to generalize the implementation of in-situ magnetic NDM [6–8] to control the mechanical and metallurgical state of high performance steels (dual-phase, TRIP and TWIP steels [9,11–13]). The mechanical behavior of these steels is highly sensitive to the thermo-mechanical history of the material (heat treatments, rolling rate…) and especially sensitive to small variations in the process (e.g. furnace temperature) [9,10]. For example, the small plastic strains experienced after a skin-pass of a dual-phase steel exhibiting a yield strength of about 450 MPa (DP780) can be easily detected by a magnetic measurement.

Plastic strain leads to strong non linear changes in the magnetic behavior [1,14–17]. Experiments performed with various carbon steels [18–23], electrical steels [16,17,24,25], iron-cobalt [26,27] or nickel alloys [1] have shown that the degradation occurs at the early stages of plastic strain [28,29]. This change of magnetic behavior (usually qualified as a “degradation” since magnetic losses are increased and permeability decreased) is associated with a change of magnetostrictive behavior [20,22,30,31] that can not be neglected in a general objective of understanding and modeling. Fig. 1 illustrates, for instance, the strong change of magnetic and magnetostrictive behavior of a common iron-silicon electrical steel submitted to a very low plastic strain after a tensile test [30].

The influence of plastic deformation on the magnetic state has been studied by many authors, some of them interested by physical mechanisms at the local scale [32,33,14], the others looking at the influence of cutting (and associated plasticity) on the global response of an electrical machine [34–36]. Interactions between the magnetic microstructure (magnetic domains and walls) and the mechanical microstructure (dislocations, grains, stress fields) are the basis of the

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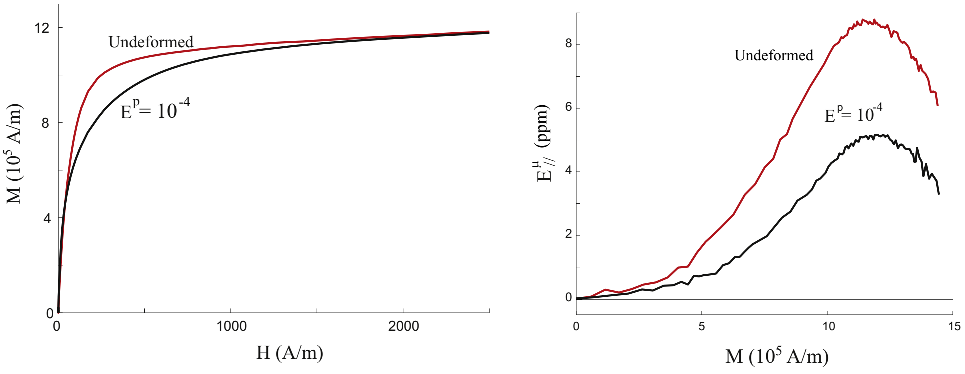

(a) magnetic behavior (b) magnetostrictive behavior

Fig. 1. Influence of a very small plastic straining (0.01%) on the anhysteretic magnetic and magnetostrictive behavior of non-oriented 3%silicon-iron [30] – quantities are defined in the next sections. (a) magnetic behavior (b) magnetostrictive behavior.

phenomenon.

The formulation of an accurate magneto-plastic coupling model provides a correlation between the plastic state and the magnetic behavior parameters. Several authors have tried to express the degradation of the magnetic state as a function of the dislocation density and pinning centers for domain walls [37,38] and to integrate it into macroscopic approaches. Indeed the microstructural defect density increases significantly with the plastic deformation (isolated dislocations, dislocation tangles and walls,..). Some phenomenological models couple the magnetic behavior and plasticity via the dislocation density [39]. However, the evolution of the dislocation density is much more regular with the accumulated plastic strain than the evolution of magnetic properties [16,17]. To represent the plastic state, other authors have thought to use the configuration of dislocations [40,41] by correlating the degradation of the magnetic state with the hardening of the material. This approach was then clarified in [17] where a link has been made between the magnetic state of a plastically deformed sample and the internal stress level. It is found that the plastic deformation is usually accompanied by a generation of internal stress. The effect of plasticity can be then interpreted as a heterogeneous strain effect, whose amplitude and wavelength depend on the microstructural configurations. This mechanical approach was not immediately retained in the scientific community. Most authors still prefer the phenomenological approaches making a link between the change of magnetic parameters (coercive field, magnetic susceptibility, core losses) to the plastic strain level [16,42,35,29] or the stress level reached during deformation [21]. The consequence is that few of these models are able to propose a complete relationship between the stress path including multiaxial state and plastic deformation and the magnetic behavior.

A micro-macro modeling has been previously proposed to reach this goal. This model describes the influence of plastic strain on the overall magneto-mechanical behavior [25,30]. It first involves a microcrystalline plasticity approach where the material is defined by its orientation distribution function (ODF). Since plastic flow is different from one grain to another due to different grain sizes and orientations, the stress field becomes heterogeneous and leads to residual stresses when the material is unloaded. The next step consisted in introducing the residual stress tensor solution of the first problem as a loading at the grain scale of a magnetic multiscale and multiaxial model able to describe magnetic and magnetostrictive behaviors [43]. This model was applied to non-oriented Fe-3%Si and simulations of the effect of plasticity are consistent with experimental observations [25,30]. However, this approach was limited to the plastic deformation range corresponding to intergranular internal stresses. In addition, only the monotonic loading was taken into account and only at the unloaded state. The principle of considering the plasticity as an internal stress state is preserved in the new proposition presented in the paper. Lastly, the challenge is to simplify the micro-macro approach to reduce the computation time for potential NDM applications and make this approach more accessible to the magnetic materials community.

In this paper a macroscopic approach for the modeling of the influence of plastic deformation on the magnetic and magnetostrictive behaviors of ferromagnetic materials is proposed. The main assumption is that the material must be considered as a two phase material, with a mechanically ”hard” phase and a mechanically “soft” phase (high and low yield strength) and appropriate volume fractions. The material is plastically strained leading to a residual stress field that can be related to the macroscopic quantity called kinematic hardening (or *kinematic strenghtening*, or *backstress*). Since stress fields are multiaxial, a magneto-mechanical equivalent stress criterion is applied to calculate the corresponding uniaxial mechanical loading [45]. The exact same two phases material is next considered for the magnetic modeling: the so-called multidomain modeling is applied to each phase as already done in [46] for Fe-Al-B alloys. Stresses calculated from the kinematic hardening and strain incompatibilities are used as loadings of the magnetic problem. The average modeling magnetic and magnetostrictive behaviors are finally obtained at a given level of plastic deformation. A superimposed macroscopic stress can be considered if appropriate.

This theoretical approach is complemented by several experiments involving magnetic and magnetostrictive measurements implemented using a DP780 steel where (mechanically) hard and soft phases are clearly defined. Results obtained using this material allow on the other hand to illustrate various points highlighted in the modeling section. Former experimental results are finally discussed in light of the proposed new approach.

2. Magnetic and mechanical states, associated variables

2.1. Magnetic state and associated variables

Magnetic materials are media which can be magnetized in presence of magnetic field. Their magnetic state can be described by the relationship between two vectors: the magnetic field $\overrightarrow{H}$ and the magnetization $\overrightarrow{M}$. The magnetic behavior is given by: $\overrightarrow{M} = \chi\overrightarrow{H}$ where χ is the second order magnetic susceptibility tensor. It depends non linearly on the magnetic field and $\overrightarrow{M}$ describes therefore a non-linear evolution as a function of $\overrightarrow{H}$. The norm of the magnetization reaches a saturation value noted M_s which is function of the material composition.

Under an alternative magnetic field, the magnetization forms a hysteresis loop illustrating the irreversibility of the magnetic behavior and the presence of dissipative phenomena. This loop is usually