Two-level model for the evaluation of hysteresis in ferromagnetic materials

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Abstract—**The magnetic hysteresis behavior of ferromagnetic materials is important to minimize material losses in electrical steels used in electrical machines and transformers. A two-level model is build to determine the influence of several microstructural features on the magnetic hysteresis behavior of a ferromagnetic work piece. In the high-level part of the model, the material is seen as an ensemble of interacting grains, where each grain is described in a low-level 3D-micromagnetic model. In this paper, we focus on the micromagnetic model. It is based on different interactions of elementary magnetic dipoles m in the grain. The time variation of the magnetic dipole m in each space point is expressed by the Landau Lifshitz equation, which is solved through time stepping in a finite difference scheme. Magnetic hysteresis loops of grains are reconstructed to see the impact of microstructural features on the shape of the hysteresis loop.**

Keywords—**hysteresis, micromagnetics, ferromagnetic materials**

I. INTRODUCTION

TO improve the performance of electromagnetic devices, like electrical machines and transformers, the overall losses in general and the iron losses in particular must be minimized. Classically, electrical steel is characterized and qualified by means of standards which are based on simple, unidirectional sinusoidal flux excitations using e.g. Epstein, ring core or single sheet measurement equipment. Generally, the measured iron losses in electromagnetic devices exceed the value based on these standard measurements. This is caused by inhomogeneities like distorted flux distributions, local rotational excitations, changes in the magnetic characteristics due to the mechanical treatment, etc. Therefore, a profound study of the material behavior of electrical steel under application conditions is very important for producers of electrical steel. Indeed, understanding the phenomena inside the electrical steel is an indispensable step in the process of developing electromagnetic devices with lower core losses, resulting in a lower energy consumption. Here, the relation between the electromagnetic behavior and the microstructure of the electrical steel is crucial as the microstructure is directly related to the material production and treatment techniques. A good description of the magnetic behavior of ferromagnetic materials starts from microstructural features like the presence of lattice effects, grains, stresses, crystal defects, etc. A physical material model becomes valuable when these microstructural features are translated into quantitative predictions about the magnetization dynamics.

II. THE TWO LEVEL MODEL

In the past, several *macromagnetic* material models where developed, mainly based on the Preisach formalism [1] or on the Jiles-Atherton algorithm [2]. They are able to describe magnetic hysteresis loops by means of a finite number of well chosen material parameters. The parameters are determined in a fitting process with experimental data. Hence, finding relations between the electromagnetic behavior and the different microstructural features of the ferromagnetic material results in numerous experiments. Moreover it is not always possible to alter a single microscopic feature without changing other microstructural properties, which is necessary to identify distinct relations between microstructure and macroscopic magnetic behavior.

On the other hand, *micromagnetic* material models are developed in the area of magnetic storage technologies, where small ellipsoidal ferromagnetic storage entities or ferromagnetic thin films are described [3, 4]. These models describe the switching process from a magnetic state corresponding with a logical 1 to a magnetic state corresponding with a logical 0 and vice versa. The simulations describe sub-micrometer monocrystals without impurities starting from their microscopic material properties. The micromagnetic models have proven to describe the magnetic dynamics in the monocrystals very accurately.

In order to describe real macroscopic ferromagnetic work pieces, a two level model is build. In this model, the material is seen as an ensemble of interacting grains. In the low level part, the dynamics of the magnetization in each grain is described on a nm scale by a 3D-micromagnetic model. Impurities like dislocations, interstitials, foreign atoms, etc are added to the micromagnetic model. In this part interactions of individual magnetic dipoles $\mathbf{m}$ with the microscopic material features on the one hand and with the magnetic field subjected to the grain on the other hand are described resulting in a mean magnetization $< \mathbf{M}_i >$ in each grain $i = 1...N$. In the high level part, each grain i interacts with the mean magnetizations $< \mathbf{M}_j >$ of all other grains $j \neq i$ and the externally applied magnetic field $\mathbf{H}_a$, resulting in an effective applied field $\mathbf{H}_{a,eff}(\mathbf{r}_i)$ for every grain. Hence, the link between the two models is the relation between the effective applied field $\mathbf{H}_{a,eff}(\mathbf{r}_i)$ felt by the grain i and the mean magnetization of the grain $< \mathbf{M}_i >$.

$$\mathbf{H}_{a,eff}(\mathbf{r}_i) \leftrightarrow < \mathbf{M}_i > \tag{1}$$

This two level model allows the simulation of magnetization loops of work pieces, starting from the microscopic material features without any experiment. It replaces the time-consuming experiments in the macromagnetic material models described above and will be used to find relations between the mentioned material parameters and the microstructure. Since the two level model relies on simulations, distinct microscopic features can be altered independently which is not possible in experiments. Next, the low level 3D-micromagnetic model will be presented.

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III. THE MICROMAGNETIC MATERIAL MODEL

The micromagnetic theory of ferromagnetic materials is based on the assumption, following Landau and Lifshitz [5], that the magnetization of magnetic dipoles **m** varies with the position, but that it has a fixed temperature dependent magnitude $|\mathbf{m}| = M_s$ (below Curie-temperature). In the theory, the Gibbs free energy (ϕ_G) represents the energy density in the grain. This energy density ϕ_G depends on the configuration of the magnetic dipoles **m** and is minimized in order to find equilibrium conditions for the magnetic dipoles, leading to the definition of the effective magnetic field ($\mathbf{h}_{eff}$) in each point of the grain.

$$\mathbf{h}_{eff} = -\frac{1}{\mu_0 M_s}\frac{\partial \phi_G}{\partial \mathbf{m}} \tag{2}$$

with μ_0 the permeability of vacuum. The static micromagnetic equilibrium is then expressed as

$$\mathbf{m}(\mathbf{r}) \times \mathbf{h}_{eff}(\mathbf{r}) = 0 \tag{3}$$

where the effective field contains the interactions with the microscopic material features and with the effective applied field $\mathbf{H}_{a,eff}(\mathbf{r}_i)$. The dynamics of the magnetic dipoles **m** is governed by the Landau-Lifshitz-equation (LL-equation), which is an extension of the static equilibrium condition (3)

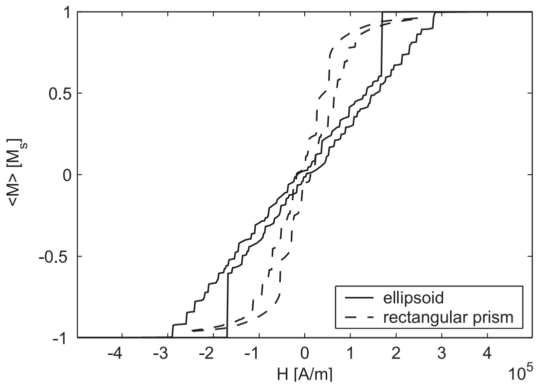
$$\frac{\partial \mathbf{m}}{\partial t} = \frac{\gamma_G}{1+\alpha^2}\mathbf{m} \times \mathbf{h}_{eff} + \frac{\alpha\gamma_G}{(1+\alpha^2)M_s}\mathbf{m} \times (\mathbf{m} \times \mathbf{h}_{eff}) \tag{4}$$

with α the damping constant and γ_G the gyromagnetic constant.

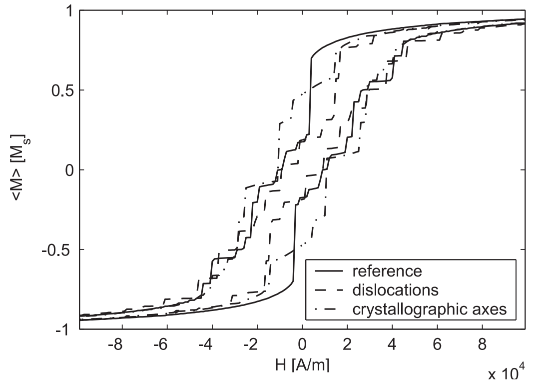
In the 3D numerical scheme, the grain is discretized in finite difference (FD) cells with edges of length Δ. Each FD cell contains one magnetic dipole **m** with a fixed amplitude M_s and varying orientation. In the grain, the crystal axes of the based centered cubic iron lattice and the impurities are defined. Time is discretized on two different levels. The effective applied magnetic field $\mathbf{H}_{a,eff}$ is discretized on a macroscopic timescale Δt of order ms and approximated with a piecewise constant time function. It is assumed that at the moment $\mathbf{H}_{a,eff}$ jumps from a constant value to the next one, each magnetic dipole **m** in the grain is in static micromagnetic equilibrium (3). In each FD cell the evolution of the magnetic dipole **m**, described by the LL-equation (4), is computed through time stepping on a timescale δt of order ps until a new static micromagnetic equilibrium is obtained corresponding with the new constant value of $\mathbf{H}_{a,eff}$. In every equilibrium point the mean magnetization $< \mathbf{M}_i >$ of the grain is computed and serves as input for the higher level.

IV. EXPERIMENTS

To show the influence of the microstructure on the magnetic properties, different experiments are performed on iron grains. For each grain the magnetic hysteresis loop is simulated. A first numerical experiment shows the influence of the shape of the grain on the hysteresis loop. In Fig. 1(a) hysteresis loops are shown for a rectangular prism of 128 × 256 × 128 FD cells with $\Delta = 9\,nm$ and an ellipsoid grain with principle axes of same dimensions. The applied field is parallel with the longest direction. The shape of the grain clearly influences the shape of the magnetic hysteresis loop. A second experiment is performed on a rectangular prism of 128 × 1024 × 128 FD cells with $\Delta = 9\,nm$. A reference grain has crystal axes parallel with the edges of the prism and the applied field parallel with the longest edge. A second grain contains in addition 10 dislocations, while in a third grain the crystal axes have a different orientation. The hysteresis loops are shown in Fig. 1(b). The presence of dislocations and the orientation of crystallographic axes clearly determine the shape of the hysteresis loop.



(a)Influence of shape



(b)Influence of crystallographic axes and dislocations

Fig. 1. Influence of microscopic features on the shape of hysteresis loops

V. CONCLUSION

A two level model to determine the influence of microstructural features on the magnetic hysteresis behavior of ferromagnetic materials is presented. The highest level describes the interactions between different grains while the lowest level describes the dynamics of individual dipoles based on the micromagnetic theory. Several experiments on grains, using the micromagnetic model, have demonstrated the influence of the microstructure on the magnetic hysteresis behavior.

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