Compumag 2015

June 28 - July 2
Montreal, Quebec

www.compumag.org

20th International Conference on the Computation of Electromagnetic Fields

Technical Program

Incorporating Hysteresis at the Grain Scale of a Multi-Scale Material Model

D. Vanoost[1,2], S. Steentjes[3], J. Peuteman[1,4], G. Gielen[5], H. De Gersem[2,6], D. Pissoort[1,5] and K. Hameyer[3]

[1]KU Leuven Technology Campus Ostend, ReMI Research Group, Oostende B-8400, Belgium
[2]KU Leuven Kulak, Wave Propagation and Signal Processing Research Group, Kortrijk B-8500, Belgium
[3]Institute of Electrical Machines, RWTH Aachen University, Aachen D-52062, Germany
[4]KU Leuven, Department of Electrical Engineering, Electrical Energy and Computer Architecture , Heverlee B-3001, Belgium
[5]KU Leuven, Department of Electrical Engineering, Microelectronics and Sensors, Heverlee B-3001, Belgium

This paper proposes a multi-scale energy based material model for poly-crystalline materials. The model considers the poly-crystalline, grain and crystal scales, exhibits magnetostriction and hysteresis and is merely based on a set of physical constants. The model is verified with existing measurement data for different stress levels and is found to provide a good accuracy.

***Index Terms*—Magnetostatics, nonlinear magnetics, magneto-mechanical couplings, hysteresis loops, multi-scale modeling.**

I. Introduction

CONTEMPORARY electrotechnical design requires highly accurate models for ferromagnetic materials which are capable of representing hysteresis and magnetostriction effects properly. This is possible using energy based material models such as the Armstrong model [1] or the multi-scale model [3], when accomplished with a hysteresis model. The Armstrong model uses an incremental hysteresis model for a single-crystal material [2]. The multi-scale model incorporates Hausers′ hysteresis model for poly-crystalline materials [4], [7]. In this paper, however, the hysteresis effect is considered at the grain scale. In contrast to [6], where artificial thresholds prevent early switching of magnetic domains, here, the grain scale magnetization of the previous time step is used for correcting the Boltzmann distribution. The new approach requires less parameters compared to the Preisach, Jiles-Atherton and Hauser models and does not demand a tedious parameter identification work, since the model is merely based on physical constants which can be looked up in standard references. Moreover, the proposed approach considers the magneto-mechanical coupling.

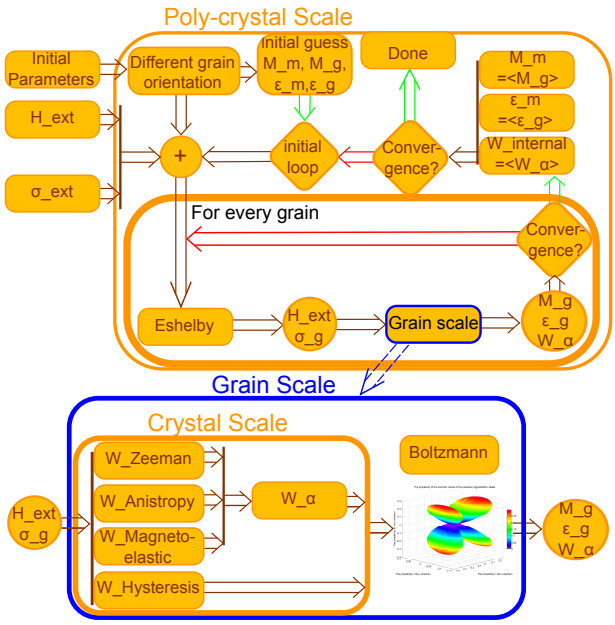

Fig. 1. Flowchart of the material model

II. Various spatial material scales

The material model uses three material scales (Fig. 1): (i) the poly-crystal scale, which is a representative volume element consisting out grains with different sizes and orientations; (ii) the grain scale, consisting of several crystals which are almost perfectly aligned to each other; (iii) the crystal scale, consisting of one perfect crystal. The poly-crystal scale takes the external magnetic field H_{ext} and the external mechanical stress σ_{ext} as inputs. The model parameters are a few physical constants and a user-defined accuracy. The initial conditions are the grain orientations and initial guesses for the mean poly-crystal scale/ grain scale magnetizations M_{m}/ M_{g} and magnetostrictive strains ϵ_{m}/ ϵ_{g}, respectively. The initial grain orientations are obtained as proposed in [8], leading to the grain scale stresses σ_{g} by solving the Eshelby inclusion problem [3], [5], [10]. Homogeneous elastic properties and a uniform strain are assumed in the grain representing the inclusion.

H_{ext} and σ_{g} are the inputs for the crystal scale, allowing to calculate the three standard energy functions [1], [3] and a new energy function modelling hysteresis (see Section II-A).

The Boltzmann distribution on the energy functions leads to the grain scale magnetizations M_{g} and magnetostrictions ϵ_{g} (see Section II-B). When M_{g} and ϵ_{g} converged, a weighted average procedure is performed, according to the Eshelby inclusion problem [3], [5], [10]. The procedure is repeated until convergence is reached at the poly-crystal scale.

A. Crystal scale

The energy functions calculated at the crystal scale are [1], [3]: (i) the Zeeman energy W_{H} based on the saturation magnetization M_{s}, (ii) the magneto-crystalline anisotropy energy W_{an} based on the crystal anisotropy constants K_1 and K_2 and (iii) the stress induced anisotropy energy W_σ based on saturation magnetostrictions λ_{100} and λ_{111}. The additional energy function modelling hysteresis is described as:

$$W_{\mathrm{hys}} = -\mu_0 \frac{M_{\mathrm{s}}}{\chi_0} \left(\alpha_{\mathrm{M1}} M_{\mathrm{hys1}} + \alpha_{\mathrm{M2}} M_{\mathrm{hys2}} + \alpha_{\mathrm{M3}} M_{\mathrm{hys3}}\right) \tag{1}$$

This energy function stands alone (see Fig. 1) and will increase the obtained anhysteresis probability, closest to grain scale magnetization in the previous time step M_{hys} (See Section II-B). Here, χ_0 is the grain scale magnetic susceptibility which is not measured as a single poly-crystal constant [3], but simulated for every grain in the first two time steps.

B. Grain scale

Due to crystal defects, not all domains have the same orientation, even in a single grain. This is taken into account by the Boltzmann distributions P_α, P_{hys} and P_{g}:

$$P_\alpha = \frac{\exp(-A_{\mathrm{s}}(W_{\mathrm{H}} + W_{\mathrm{an}} + W_\sigma))}{\int_\alpha \exp(-A_{\mathrm{s}}(W_{\mathrm{H}} + W_{\mathrm{an}} + W_\sigma))} \tag{2}$$

$$P_{\mathrm{hys}} = \frac{\exp(-\beta A_s W_{\mathrm{hys}})}{\int_\alpha \exp(-\beta A_{\mathrm{s}} W_{\mathrm{hys}})} \tag{3} \qquad P_{\mathrm{g}} = \frac{P_\alpha P_{\mathrm{hys}}}{\int_\alpha P_\alpha P_{\mathrm{hys}}} \tag{4}$$

The standard Boltzmann distribution P_α includes the parameter $A_s = (3\chi_{m0})/(\mu_0 M_s^2)$ as a measure for the regularity of the crystal. In this paper, the poly-crystal scale magnetic susceptibility χ_{m0} is replaced by the grain scale susceptibility χ_0. The additional energy function (1), in the crystal scale, models the hysteresis by increasing the obtained anhysteretic probability (2) (using the three standard energy functions), closest to M_{hys}. An additional Boltzmann distribution P_{hys} with a correction factor β (here set to 1.2, 1 and 0.9 for respectively 0, -25 and -50 MPa) is introduced. The correction factor β models the pinning effect, as suggested by Hauser [7], which was not considered for obtaining A_{s} in [3]. The combination of both (see (4)) allows to predict M_{g} and ϵ_{g} as in [1] and [3], but with inclusion of the hysteresis effect. The method is valid for alternating as well as for rotating magnetic fields.

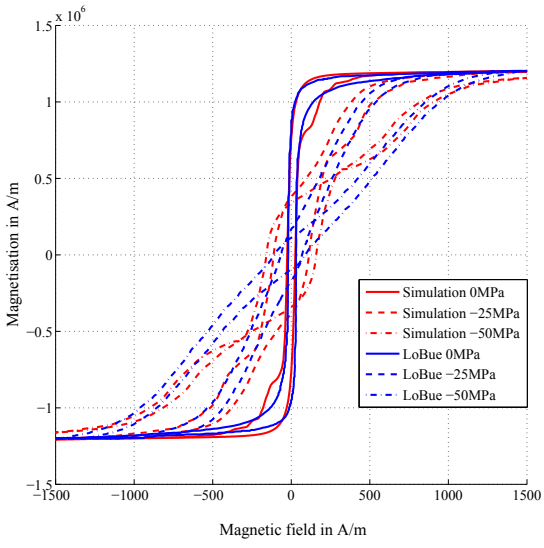

Fig. 2. Comparison between the results from the model, indicated in red, and the reference results reported in [9], indicated in blue.

III. Validation

The simulated results are compared to measurements on Fe-Si3% reported in [9]. Fig. 2 shows that the results from the model, indicated in red, are in good agreement with the reference results, indicated in blue. The remaining differences are attributed to unknown internal stresses, possibly introduced by the manufacturing process.

IV. Conclusion

An energy based material model is extended by a hysteresis model inserted at the grain scale. Although based on a small set of parameters, the extended model shows a good agreement for a poly-crystalline material with this approach it's possible to link micro- and macroscale effects by a reliable model.

V. Acknowledgements

This PhD research is funded by the "Agency for Innovation by Science and Technology in Flanders (IWT)", by a "Travel Grant for a long stay abroad" of the Research Foundation - Flanders (FWO).

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