Journal of Magnetism and Magnetic Materials 414 (2016) 168–179

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Magnetic hysteresis at the domain scale of a multi-scale material model for magneto-elastic behaviour

D. Vanoost [a,b,*], S. Steentjes [c], J. Peuteman [a,d], G. Gielen [e], H. De Gersem [b,f], D. Pissoort [a,e], K. Hameyer [c]

[a] KU Leuven Technology Campus Ostend, ReMI Research Group, Oostende B-8400, Belgium
[b] KU Leuven Kulak, Wave Propagation and Signal Processing Research Group, Kortrijk B-8500, Belgium
[c] Institute of Electrical Machines, RWTH Aachen University, Aachen D-52062, Germany
[d] KU Leuven, Department of Electrical Engineering, Electrical Energy and Computer Architecture, Heverlee B-3001, Belgium
[e] KU Leuven, Department of Electrical Engineering, Microelectronics and Sensors, Heverlee B-3001, Belgium
[f] TU Darmstadt, Institut für Theorie Elektromagnetischer Felder, Darmstadt D-64289, Germany

ARTICLE INFO

Article history:
Received 27 July 2015
Received in revised form
8 March 2016
Accepted 11 April 2016
Available online 30 April 2016

Keywords:
Magnetostatics
Nonlinear magnetics
Magneto-mechanical couplings
Hysteresis loops
Multi-scale modelling
Micro-magnetics

ABSTRACT

This paper proposes a multi-scale energy-based material model for poly-crystalline materials. Describing the behaviour of poly-crystalline materials at three spatial scales of dominating physical mechanisms allows accounting for the heterogeneity and multi-axiality of the material behaviour. The three spatial scales are the poly-crystalline, grain and domain scale. Together with appropriate scale transitions rules and models for local magnetic behaviour at each scale, the model is able to describe the magneto-elastic behaviour (magnetostriction and hysteresis) at the macroscale, although the data input is merely based on a set of physical constants. Introducing a new energy density function that describes the demagnetisation field, the anhysteretic multi-scale energy-based material model is extended to the hysteretic case. The hysteresis behaviour is included at the domain scale according to the micro-magnetic domain theory while preserving a valid description for the magneto-elastic coupling. The model is verified using existing measurement data for different mechanical stress levels.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

Modelling of ferromagnetic material behaviour is commonly done using microscopic approaches based on the Landau–Lifschitz–Gilbert equation or using macroscopic models with constitutive laws identified from macroscopic measurements. However, these attempts are either unfeasible for modelling macroscopic structures or do not consider the heterogeneity and multi-axiality of the material behaviour.

Contemporary electro-technical design requires highly accurate models for ferromagnetic materials. They should be capable of representing hysteresis and magnetostriction effects properly. Moreover, they should consider the multi-axiality and heterogeneity of the material behaviour. Finally, it should be possible to extract macroscopic effective properties from the constituent properties, local anisotropy and crystallographic texture. A multi-scale material model, connecting various spatial material scales upholding strong physical connections while remaining applicable as a design tool, is required.

In 1865 Villari found the correlation between a magnetisation change and the tensile stress of iron-based materials [34,43], known as the *Villari effect* [12]. Buckley showed in 1925 [8] that a mechanical stress has a non-negligible impact on the magnetic material properties. It affects both the size as well as the shape of the hysteresis loop, i.e., the extrinsic properties coercivity and remanence [7,8,13,16,28–30,38,35].

The internal mechanical stress can originate from: (i) the manufacturing process [5]; (ii) a heating or a cooling step [39]; (iii) the operation of the electrical device (e.g. centrifugal forces due to the high-rotational speed) [6]; or (iv) the magnetostriction in a poly-crystalline material [14].

In order to account for the magneto-elastic coupling two approaches can be distinguished based on their underlying physical assumptions.

1. Phenomenological macroscopic models predict the magnetic behaviour at the *poly-crystalline scale* introducing the mechanical stress as a parameter in a classical macroscopic hysteresis

* Corresponding author at: KU Leuven Kulak, Wave Propagation and Signal Processing Research Group, Kortrijk B-8500, Belgium
E-mail address: dries.vanoost@kuleuven-kulak.be (D. Vanoost).

http://dx.doi.org/10.1016/j.jmmm.2016.04.028
0304-8853/© 2016 Elsevier B.V. All rights reserved.

model, e.g., the *Jiles–Atherton–Sablik* model [37] or the *Preisach* model [1]. Other macroscopic models use thermodynamic arguments [24] as an additional macroscopic energy term including the magneto-elastic effect. Their disadvantages are: (i) the small working range, (ii) only representing isotropic materials, (iii) requiring tedious parameter identifications and (vi) mostly excluding multi-axial mechanical stresses. This means that they are acceptable for standard magnetic materials in traditional situations and are comparably simple with fast computations, but not appropriate as an investigation tool to optimize materials in specific designs. Moreover, they neglect the subtle coupling of magnetostriction and the magneto-elastic effect by excluding the knowledge of the internal domain structure and the crystallographic magnetic texture.
2. Micro-magnetic models predict the magnetic behaviour at the *domain scale* and/or the *grain scale*. The magnetic domain behaviour, investigated by the energy density functions, represents the potential energy of the investigated crystal [18,32,42]. The minimum of the energy density functions defines current magnetic state being affected by a internal mechanical stress and a magnetic field. Among others, Armstrong [2] and DeSimone and James [17], use uni-axial and cubic crystalline symmetries in magneto-elastic simulations. These simulations are done on the domain structure limiting the approach in size to reduce the computational cost.

The aforementioned strategies are either of limited prediction range or difficult to manage to predict the result of the intricate magneto-elastic coupling of a poly-crystalline material for arbitrary mechanic stresses (vectorial, compressive, tensile).

In contrast, multi-scale methods are able to resolve the complexity of the magneto-elastic coupling by enriching the macroscopic material description by observations at various spatial scales. Describing the behaviour of poly-crystalline materials at different spatial scales allows distinguishing between dominating physical mechanisms and accounting for the heterogeneity and multiaxiality of the material behaviour. Together with appropriate scale transitions rules and models for the local magnetic behaviour at each scale, the model is able to describe the magneto-elastic behaviour (magnetostriction and hysteresis) at the macroscale although the data input is merely based on a set of physical constants.

This is possible using energy-based material models such as the Armstrong model [2] or the multi-scale model [15], when accomplished by a static hysteresis model. The Armstrong model uses an incremental hysteresis model for a single-crystal material [4], i.e., hysteresis is included for a fixed crystal direction by calculating the losses due to the crystal defects. In contrast the originally anhysteretic multi-scale approach presented in [15] is extended to the hysteretic case using the Hauser energetic model for ferromagnetic hysteresis for the description of poly-crystalline materials [16,21]. Hysteresis is obtained by adding an irreversible magnetic field to the anhysteretic field component obtained by the anhysteretic multi-scale model [15]. This approach requires four additional free parameters identified by a tedious parameter identification. The multi-scale approach in [15] is based on the results of the multi-scale approach of: (i) poly-crystalline materials for structural mechanic simulations [23] and (ii) ferroelectric poly-crystallines [25], which are included in the non-linear behaviour of a heterogeneous material.

In this paper, however, the hysteresis effect is implemented at the domain scale for a poly-crystalline isotropic material. In contrast to [20], where artificial thresholds prevent early switching of magnetic domains, the Boltzmann distribution is extended using the *grain scale* magnetisation of the previous time step for correcting the statistical distribution of magnetic domains in the new energy density function. This approach requires less parameters compared to the Preisach [10], Jiles–Atherton [44] and Hauser [21] models, while including the effect of the mechanical stress on the hysteresis and does not demand a tedious parameter identification work.

The paper is organised as follows. Section 2 introduced the definition of the three different spatial material scales used to account for the magneto-elastic coupling affected by the different grain orientations in a poly-crystalline material as discussed in Section 3. Section 4 discusses the multi-scale model posed by Eshelby inclusion problem and the scale transitions rules mapping between the *domain scale*, the *grain scale* and the *poly-crystalline scale*. Section 4.2 describes the three standard energy density functions of micromagnetism, i.e., Zeemann, magneto-crystalline anisotropy and magneto-elastic energy. In addition, the proposed energy density function for inclusion of magnetic hysteresis at the domain scale is presented. The model is validated in Section 5 using measurements and physical theories both available in literature. The paper ends with some conclusions.

2. Various spatial material scales

The multi-scale material model iterates between three different spatial material scales to represent the magnetic behaviour of the poly-crystalline material. The scales are the *poly-crystalline scale*, the *grain scale* and the *domain scale*, see Fig. 1.

1. The *poly-crystalline scale* (0.1–50 mm) is a representative volume element [15], i.e., it represents the macroscopic material properties of the considered material. The *poly-crystalline scale* contains different, randomly oriented grains. Each grain contributes to the macroscopic behaviour.
2. One grain (1 μm–10 mm) consists of multiple crystals, which are almost perfectly aligned with each other. The *grain scale* considers homogeneous elastic properties and a uniform strain [15]. The grain magnetisation is determined by the magnetic domains in the grain.
3. A magnetic domain (0.1–1 μm forms a substructure of the grain structure. Inside a magnetic domain both the mechanic as well as magnetic quantities are homogeneous, forming the smallest scale of the multi-scale scheme. Depending on the crystal structure, i.e., the crystal system, (i) body centred cubic (bcc) crystal, (ii) the face centred cubic (fcc) crystal, (iii) the hexagonal crystal, easy and hard magnetization directions are formed defining the direction of spontaneous domain magnetization in the demagnetized state [7,9,10,12].

3. Different grain orientations – crystallographic texture

The relation between the magnetic and mechanic properties at the three different spatial scales is defined by a combination of localisation and homogenisation operations. Therewith it is possible to calculate the magnetisation and magnetostriction of a material point at the *poly-crystalline scale* accounting for the intricate magneto-elastic coupling ruled by characteristics described at different spatial scales.

The external magnetic field H_{ext} and mechanical stress σ_{ext} act on the *poly-crystalline scale* and are described in the same reference frame, called the poly-crystalline reference frame. This reference frame is the main reference frame in the material model. The other reference frames used at the *grain scale* are determined by the different grain orientations. In contrast to [15], the magnetic field acting at the *grain scale* is not transformed in a localisation scheme to include the effect of the demagnetisation field,

Download English Version:

https://daneshyari.com/en/article/1797979

Download Persian Version:

https://daneshyari.com/article/1797979

Daneshyari.com