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A numerical study on magnetostrictive phenomena in magnetorheological elastomers

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ABSTRACT

Herein, we present an investigation on magnetostrictive phenomena in magnetorheological elastomers. By using a continuum approach, constitutive as well as geometric properties on the microscale are taken into account in order to predict the effective behavior of these composites by means of a computational homogenization. Thus, the magnetic and mechanical fields are resolved explicitly without the simplifying assumption of dipoles. In the present work, a modeling strategy which accounts for elastic constituents and a nonlinear magnetization behavior of the particles is pursued. In order to provide a better understanding of fundamental deformation mechanisms, idealized lattices as well as compact and wavy chains are considered within a first study. Our results confirm assumptions stated in the literature according to which macroscopic magnetostriction can be ascribed to microscopic particle movements that result in an improved microstructure. The simulations that are performed for the subsequent investigations on random microstructures with different particle-volume fractions are evaluated statistically to ensure validity of our findings. They reveal anisotropic as well as isotropic macroscopic behavior for structured and unstructured particle distributions, respectively. In view of the macroscopic magnetostriction, all the results presented in this contribution are in good agreement with current experimental and theoretical findings.

1. Introduction

Magnetorheological elastomers (MREs) typically represent a two-component system consisting of micron-sized magnetizable particles embedded into a non-magnetizable polymer matrix. Due to particle-particle interactions on the microscopic scale these materials can alter their macroscopic behavior reversibly when subjected to an external magnetic field, which makes them attractive to several engineering applications such as actuators and sensors [45,50], valves [3] or tunable vibration absorbers [5]. The macroscopic properties of MREs are essentially determined by the underlying microstructure that results from the manufacturing process. Depending on whether a magnetic field is applied during the cross-linking process of the polymer matrix, the spatial distribution of the particles can be either structured or unstructured which leads to anisotropic and isotropic material behavior, respectively. Commonly, structured MREs feature chain-like particle distributions generated by a uniaxial magnetic field. Martin et al. [37,36] also show that more complex structures including sheets, networks and honeycombs can be generated by combining rotating and uniaxial magnetic fields.

Present theoretical investigations on MREs can be divided into microscopically motivated and phenomenological approaches. Particle-interaction models as used by Cremer et al. [7], Han et al. [21], Ivaneyko et al. [28,26,27], Jolly et al. [31], and Pessot et al. [40] are based on the calculation of macroscopic material properties from energetic terms that are found by making several limiting assumptions. One advantage of such a modeling strategy is that the underlying microstructure can be considered without the need to explicitly resolve the local magnetic and mechanical fields. However, the frequently used approximation of each particle being a point dipole is only appropriate if the system is dilute, which is not the case for many MREs with practical use. A possible extension of particle-interaction models to higher particle volume fractions is shown by Biller et al. [2] who are using a multipole expansion in order to calculate the spatial distribution of the magnetization within the particles. Another microscopically motivated approach is presented in the works of Galipeau and Ponte

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Castañeda [15,16], Javili et al. [30], Keip and Rambausek [33], Ponte Castañeda and Galipeau [41], Schröder et al. [44] as well as Spieler et al. [46,47]. Here, the local magnetic and mechanical fields are resolved explicitly by using a continuum formulation of the coupled magnetomechanical problem. The effective material behavior of the MRE is then calculated by applying an appropriate homogenization scheme. Since each of the constituents is considered separately within this modeling strategy, influences of the microstructure can be taken into account. Hence, deformation mechanisms presumably leading to characteristic phenomena like magnetostriction and the magnetorheological effect can be investigated systematically. Additionally, there is the possibility to analyze the stability of magnetoactive materials under different loading conditions as performed in the work of Rudykh and Bertoldi [43] for an idealization of MREs with a chain-like microstructure.

In phenomenological approaches as used in Bustamante [4], Dorfmann and Ogden [10,12], Han et al. [21], Miehe et al. [38], Kankanala and Triantafyllidis [32] as well as Raikher and Stolbov [42] the material model is fitted to experimental data or results obtained from a homogenization. Since the MRE is treated as a homogeneous composite, microstructural effects cannot be investigated within this modeling strategy. The advantage of such an approach is its wide range of applications. While it is impossible to model geometric details to the microscopic level with reasonable effort, the phenomenological approaches can be used to predict the behavior of real structures under complex loading conditions [22]. Moreover, these models allow for a straightforward generalization towards more complex materials as it is shown in the works of Miehe et al. [38,39] and Kiefer et al. [35,34] for electro-magnetomechanical and rate-dependent problems, respectively.

As the basis for a variety of applications, magnetostriction is one of the most interesting and therefore most studied phenomena associated with magnetoactive materials. Originally designating strains generated by an applied magnetic field due to a reorientation of magnetic moments, this term indicates a significantly larger deformation response caused by particle-particle interactions in the context of MREs. Besides shape, size and volume fraction, the distribution of the particles has a considerable influence on the magnetostrictive behavior of the material. Experimental investigations made by Guan et al. [20], Han et al. [22], Stepanov et al. [48] as well as Zhou and Jiang [52] show that unstructured samples elongate in the direction of the applied magnetic field which is verified by the theoretical works of Galipeau and Ponte Castañeda [15] and Galipeau et al. [17]. However, for structured samples with a chain-like distribution of particles Danas et al. [8], Ginder et al. [18], Guan et al. [20], and Han et al. [22] measure an elongation of the specimen while Coquelle and Bossis [6] as well as Zhou and Jiang [52] state that the MRE tends to contract in the direction of the magnetic field. The same contradiction exists in theoretical findings – Zubare [53] predicts elongation whereas Ivaneyko et al. [25] calculate a contraction of the sample.

The aim of this work is a thorough investigation on magnetostrictive phenomena in MREs based on a microscopically motivated continuum model. For the calculation of the effective material behavior the homogenization scheme presented in Spieler et al. [46] is used. In order to understand deformation mechanisms on the microscale that are leading to magnetostriction, samples with different particle distributions are considered. Within a first study, the deformation behavior of idealized microstructures is examined. The findings of this study are utilized to explain effects leading to magnetostriction in the subsequent analysis of more realistic microstructures. The results are evaluated statistically for structured and unstructured MREs with different particle-volume fractions in order to account for influences of the particle distribution.

The organization of the paper is as follows: in Section 2 the modeling of MREs within the framework of a continuum formulation of the coupled magnetomechanical problem is described. Basic equations as well as experiments helping to characterize the constitutive behavior and the structure of real MREs are presented. The findings of the study on idealized microstructures which includes hexagonal and square lattices as well as different chain-like arrangements are shown in Section 3 while the analysis of samples with more realistic particle distributions is the integral part of Section 4. After a discussion of the results, the paper is closed by some concluding remarks and an outlook to necessary future work.

Throughout this article, index notation with respect to a Cartesian frame and the Einstein summation convention will be applied in equations, whereas vectors and higher-order tensors will be denoted by boldface italic symbols within the text. Additionally, δ_{kl} and e_{klm} will be used to announce the Kronecker delta as well as the third order permutation symbol. Following the concept of a continuum, the material body occupies the domain $\mathcal{B}$ with volume V and boundary $\partial\mathcal{B}$. Partial derivatives of a field quantity $(\cdot)$ with respect to the position vector x_k and the jump of this quantity across a surface of discontinuity $\mathcal{S}_\mathrm{d}$ with a unit normal vector $\boldsymbol{n}$ pointing from the subdomain $\mathcal{B}^-$ to $\mathcal{B}^+$ will be identified by $(\cdot)_{,k}$ and $[\![(\cdot)]\!] = (\cdot)^+ - (\cdot)^-$, respectively.

2. Modeling of MREs

In this section, the modeling of magnetoactive materials by means of a microscopically motivated continuum formulation will be outlined. To this end, the governing equations of the stationary magnetic and the coupled mechanical boundary value problems (BVPs) are introduced. Additionally, constitutive models are developed for the polymer matrix and the magnetizable particles. In order to characterize the microstructure of real MREs, experimental data of a particle distribution are presented. Finally, a computational homogenization scheme based on a solution of the coupled problem using the finite element method is described.

2.1. Stationary magnetic BVP

According to Jackson [29], the continuum formulation of the electrodynamic BVP is given by Maxwell's macroscopic equations. For the stationary case, the electric and magnetic fields decouple so that the magnetic problem is described by the following set of differential equations and jump conditions:

$$B_{k,k} = 0 \quad \text{in } \mathcal{B} \quad \text{with} \quad [\![B_k]\!]n_k = 0 \quad \text{on } \mathcal{S}_\mathrm{d}, \tag{1}$$

$$e_{klm}H_{m,l} = j_k \quad \text{in } \mathcal{B} \quad \text{with} \quad e_{klm}[\![H_m]\!]n_l = k_k \quad \text{on } \mathcal{S}_\mathrm{d}. \tag{2}$$

Herein, the field quantities $\boldsymbol{B}, \boldsymbol{H}$ and $\boldsymbol{j}$ denote the magnetic induction, the magnetic field strength and the vector of free current density, respectively. Across a surface of discontinuity, the normal component of $\boldsymbol{B}$ has to be continuous. Analogously, Eq. (2) shows that the tangential component of $\boldsymbol{H}$ is continuous in case of a vanishing current density $\boldsymbol{k}$. Determining the magnetic state of the material, the magnetization $\boldsymbol{M}$ is connected to the magnetic induction and the magnetic field by the relation

$$B_k = \mu_0(H_k + M_k), \tag{3}$$

in which $\mu_0 = 4\pi \times 10^{-7}$ N A^{-2} represents the permeability of free space. In order to solve both of the differential equations in (1) and (2), the magnetic vector potential $\boldsymbol{A}$ is introduced. By defining

$$B_k = e_{klm}A_{m,l} \tag{4}$$

and using the Coulomb gauge $A_{k,k} = 0$, Gauss's law for magnetism is satisfied automatically whereas Ampère's circuital law stated in Eq.