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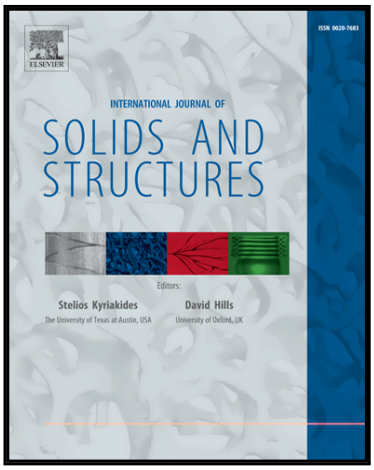

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Microscale modeling and simulation of magnetorheological elastomers at finite strains: A study on the influence of mechanical preloads

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Abstract

Herein, we present a numerical study on the deformation dependent behavior of magnetorheological elastomers with structured and unstructured particle distributions. To this end, finite element simulations are performed in order to calculate the effective magnetization and macroscopic actuation stresses for different specimens with realistic microstructures and varying mechanical preloads. Since the proposed microscale model is based on a continuum formulation of the magnetomechanical boundary value problem, the local magnetic and mechanical fields are resolved explicitly within the microstructures. The consideration of finite strains results in a finite element implementation of the coupled field problem for which a consistent linearization scheme is presented. In order to provide a better understanding of the deformation dependent behavior in real specimens, a study on chain-like structures is performed. It reveals that the interaction of the constituents in chain-like structures yields different material responses depending on their position. These findings are used to explain the influence of mechanical preloads on the behavior of samples with structured and unstructured arrangements of the particles. All of our results are in good agreement with experimental investigations which have been carried out for magnetorheological elastomers comprising a structured particle distribution.

Keywords: Finite element method, Finite strains, Magnetoelasticity, Magnetomechanical coupling

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1. Introduction

Magnetorheological elastomers (MREs) are composite materials which consist of micron-sized magnetizable particles that are embedded into a non-magnetizable polymer matrix. Due to mutual interactions of the constituents on the microscopic scale, these materials can alter their macroscopic behavior reversibly if an external magnetic field is applied. This makes them attractive to several engineering applications such as actuators and sensors (Schubert, 2014; Tian et al., 2011), valves (Böse et al., 2012) or tunable vibration absorbers (Carlson and Jolly, 2000). The macroscopic properties of MREs are essentially determined by the underlying microstructure which is a result of the manufacturing process. In their work, Ginder et al. (1999) show that the presence of a magnetic field during the crosslinking of the polymer matrix promotes the formation of chain-like microstructures with an anisotropic response, whereas unstructured particle distributions with an isotropic material behavior are the result, if the magnetic field is omitted.

Different macroscopic phenomena are associated with magnetoactive elastomers and therefore studied extensively in theory and experiments. The magnetorheological (MR) effect designates a variation of the elastic modulus in an external magnetic field. Experimental investigations by Borin et al. (2013) and Jolly et al. (1996) reveal a positive MR effect, i. e. an increasing elastic modulus, for unstructured MREs. Han et al. (2015) find an even stronger effect for materials with a structured particle distributions. If the experimental setup allows for a deformation of the specimen, the magnetostrictive (MS) effect can be observed. Studies performed by Zhou and Jiang (2004), Guan et al. (2008), Han et al. (2015) as well as Stepanov et al. (2008) show that unstructured samples elongate in the direction of the magnetic field which is verified by the theoretical work of Galipeau and Ponte Castañeda (2012). For structured samples with a chain-like distribution of particles, Ginder et al. (2002), Guan et al. (2008) and Han et al. (2015) also measure an elongation of the specimen. Furthermore, the work of Danas et al. (2012) demonstrates a strong dependence of the MS effect on applied mechanical preloads.

The modeling of MREs can be divided into microscopically and phenomenologically motivated approaches. Particle-interaction models as used by Cremer et al. (2015), Han et al. (2013), Ivaneyko et al. (2012, 2014), Jolly et al. (1996) and Pessot et al. (2014) are based on a minimization of energetic terms which can be found by assuming that the magnetizable particles are dipoles. A crucial advantage of this modeling strategy is the possibility to consider the underlying microstructure although the local magnetic fields are not resolved explicitly. However, the assumption of dipoles is only appropriate if the system is dilute, which is often not the case for MREs. According to Biller et al. (2014), this problem can be solved by applying a multipole expansion in order to calculate the spatial distribution of the magnetization. Another microscop-

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