EXPERIMENTS AND MODELING OF MAGNETORHEOLOGICAL ELASTOMERS WITH PARTICLE-CHAIN MICROSTRUCTURES

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Summary Magnetorheological elastomers (MREs) are ferromagnetic particle impregnated elastomers whose mechanical properties are altered by the application of external magnetic fields. Due to their magnetoelastic coupling response, MREs are finding an increasing number of engineering applications. The objective of this work is (a) the experimental study of transversely isotropic MREs (i.e., particles form chains along a certain direction) that are subjected to prestressing and arbitrary magnetic fields and (b) the continuum modeling of these materials using transversely isotropic energy functions. In addition, full-field FEM calculations are carried out in order to reveal the underlying deformation micro-mechanisms that lead to the observed macroscopic magnetostriction of the MRE.

INTRODUCTION

Devices made of magneto-rheological elastomers (MREs) have been proposed for a number of engineering applications due to the potentially controllable nature of their mechanical properties [1]. Although there has been a substantial effort in theoretical descriptions of these types of solids (e.g., [3], [5]), there have not been many studies–to the best knowledge of the authors–dealing with the constitutive modeling and characterization of MREs. Material models for other magnetoelastic solids, however, have been presented in the literature. For example, [7] gave the first characterization of Terfenol-D. In this regard, due to the absence of adequate constitutive description for MREs, it has been difficult to quantify the extent of benefits that a MRE device could offer. The objective of this work is twofold; first, we present experiments of iron-particle-filled elastomers subjected to prestressing and arbitrary magnetic fields and second, we propose an energy density function that is able to reproduce the experimental measurements. In order to explain the deformation micro-mechanisms leading to the overall magnetostriction of the composite, we also carry out full-field coupled FEM microstructural calculations.

EXPERIMENTS AND MODELING

Experiments are carried out [2] for MREs comprising 25% of iron particles of sizes ranging from $0.5\mu m$ to $5\mu m$ cured in a 0.8T magnetic field. The application of a magnetic field during the curing process leads to formation of particle chains aligned with the curing field direction. The experiments involve three different setups; (a) uniaxial stress tests in the direction of a magnetic field which is aligned with the particle chains, (b) uniaxial stress tests in the direction of a magnetic field which is perpendicular to the particle chains and (c) simple shear tests where the particle chains are initially aligned with the applied magnetic field, as shown in Fig. 1.

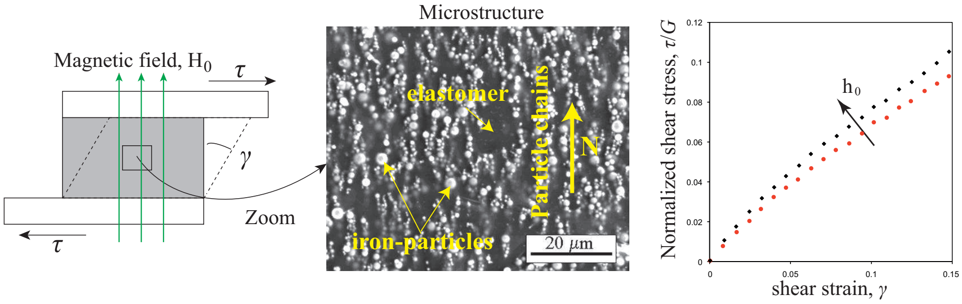

Figure 1. An illustration of the stiffening effect of a magnetic field on the shear stress-strain behavior of a MRE (left) with particle-chain microstructure, initially aligned with the applied magnetic field (center). The stiffening in the mechanical response when a magnetic field $\mathbf{h}_0$ is applied is due to inter-particle magnetic forces (right).

The second part of this work pertains in finding an energy density function $\widehat{\psi}$ that best fits the experiments reported above [2]. The material under investigation is a transversely isotropic composite since the iron particles form chains along a certain direction. This implies that the free energy density $\widehat{\psi}$ should also depend on the unit vector $\mathbf{N}$, (see Fig. 1), which defines the initial orientation of the particle chains. Thus,

$$\widehat{\psi} = \widehat{\psi}(\mathbf{C}, \mathbf{N}, \mathbf{M}), \quad \mathbf{C} = \mathbf{F}^T \bullet \mathbf{F}, \quad \mathbf{N} \bullet \mathbf{N} = 1, \tag{1}$$

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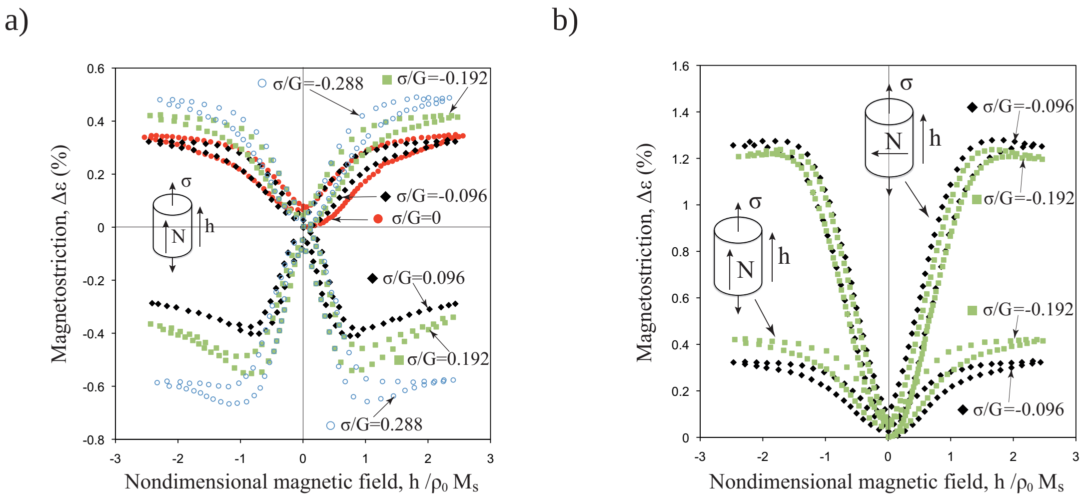

Figure 2. Magnetostriction $\Delta\varepsilon$ versus the applied nondimensional magnetic field $h/\rho_0 M_s$ for various prestresses, σ/G, aligned with the applied magnetic field. Part (a) and (b) correspond particle chains parallel ($\mathbf{h} \parallel \mathbf{N}$) and perpendicular ($\mathbf{h} \perp \mathbf{N}$), respectively, to the applied magnetic field.

where $\mathbf{F}$ is the material's deformation gradient ($\mathbf{F}^T$ denotes its transpose), $\mathbf{C}$ denotes the right "Cauchy-Green" tensor and $\mathbf{M}$ the specific magnetization. Fig. 2 shows experimentally measured magnetostriction strain $\Delta\varepsilon$ versus the applied nondimensional magnetic field $h/\rho_0 M_s$ for uniaxial stress tests (with ρ_0 denoting the initial material density). In Fig. 2a, the magnetostriction is plotted for different preloads σ/G, which are aligned with the applied magnetic field and the particle chain ($\mathbf{h} \parallel \mathbf{N}$). The magnitude of magnetostriction increases in absolute value with the magnitude of the nondimensional preloads. Interestingly, the magnetostriction response is not symmetric with respect to the sign of the prestress in Fig. 2a. Notice that the sample expands ($\Delta\varepsilon > 0$) for zero or negative prestresses and contracts for adequately large tensile prestresses. This asymmetry implies a strong nonlinear effect of the applied prestress on the resulting magnetostriction. In turn, Fig. 2b, shows the strong influence of the particle-chain orientation upon the overall magnetization and magnetostriction of the MRE specimens. In order to unfold the corresponding underlying microstructural deformation mechanisms leading to the pronounced prestress and particle-chain orientation effects, FEM full-field calculations are also carried out (not shown here for brevity). Theoretical predictions, based on the energy density of equation (1) are compared to experimental results in the case of simple shear loading and a uniaxial stress test in the direction of a magnetic field which is (i) aligned with the particle chains and (ii) perpendicular to the particle chains (not shown here for brevity). In all three cases, the model predicts well the experimental response of the MRE.

CONCLUSIONS

The present combined experimental and theoretical investigation of MREs subjected to coupled mechanical and magnetic loading reveals the many challenging features of these materials. This study shows the adequacy of the anisotropic, finite strain continuum formulation for the description of these materials, while at the same time it demonstrates the importance of microgeometry in the macroscopic magnetoelastic coupling response of the composite. Given the need in applications to produce MREs with strong magnetoelastic coupling, it is desirable to build a) microscopic models to study these coupling mechanisms in detail and b) mean-field (i.e., homogenization) models to investigate more efficiently the influence of matrix properties, particle distribution and shape on the macroscopic magnetomechanical response of these composites. On the practical side, mean field theories are a valuable tool to optimize coupling properties (e.g., [4, 6]) in these materials. Studies in these directions are currently under way by the authors.

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