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Continuum-based modeling of hard-magnetic magneto-active polymers across the scales

Author: Philipp Gebhart[1]

Co-author: Thomas Wallmersperger [1]

[1] *TU Dresden*

Field-responsive functional composite materials have attracted growing interest in recent theoretical and experimental research. Magneto-active polymers (MAPs) constitute a particular class of such field-responsive solids, consisting of a polymeric matrix embedded with dispersed, micro-sized magnetizable particles. Depending on the magnetic characteristics of the ferromagnetic filler, MAPs are commonly categorized as (i) soft magnetic MAPs and (ii) hard magnetic MAPs. Soft magnetic MAPs, containing particles such as carbonyl iron, exhibit negligible hysteresis losses and complete demagnetization upon field removal, giving rise to fully reversible deformation. In contrast, hard magnetic MAPs filled with NdFeB particles show pronounced nonlinear and dissipative behavior, including sigmoid-shaped magnetic hysteresis and butterfly-shaped field-induced strain hysteresis. This work presents a comprehensive variational-based modeling framework for hard magnetic MAPs, with soft magnetic MAPs recovered as a limiting case. The constitutive theory is cast within the framework of generalized standard materials, requiring definitions of (i) the total energy density and (ii) the dissipation potential. A key feature is the additive decomposition of the material energy into contributions from (i) elastic stress in the absence of a magnetic field, (ii) magnetization, and (iii) magnetically induced mechanical stresses. Within this energy-based framework, constitutive functions are proposed that accurately capture the highly nonlinear response of hard magnetic MAPs with stochastic microstructures. These relations are embedded in a time-discrete variational minimization principle and paired with an efficient conforming finite element method. The polyconvexity of the model is examined, implying quasiconvexity and rank-one convexity, thereby ensuring material stability.
The framework's predictive capability is demonstrated through application-oriented three-dimensional boundary value problems, focusing on macroscale magnetostrictive effects and pre-magnetized beam structures undergoing large deformations.

References

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