Call for PhD candidates (with possibly a master's internship beforehand)

Investigation of three-dimensional instabilities in magneto-active thin films heterogeneously patterned by design

This thesis is part of a joint project with the University of Stuttgart, funded by the ANR (French National Research Agency), and proposing to investigate and exploit experimentally, theoretically, and numerically, the instabilities inherently present in magnetorheological elastomer-based materials and structures.

General background of the project

Magnetorheological Elastomers (MREs) are smart materials comprising magnetizable particles embedded in an elastomer matrix. They readily respond to the application of a magnetic field, either by exhibiting magneto-induced large deformations [**Bod18**] or by displaying large displacements induced by structural instabilities (that are linked to the magnetic compass effect or to combined magneto-mechanical compressive stresses). In particular, in a system made of a *uniform* MRE film bonded to a non-magnetic substrate, instabilities can be triggered by mechanical loading, magnetic loading or a combination of both, thus yielding periodic wrinkling as displayed in Fig. 1a [**Psa17**] or more complex profiles, such as crinkling [**Psa19**]. Such controllable instabilities were demonstrated both experimentally and numerically [**Psa17**] but remained limited to 2.5D patterns, that is a profile extruded in one direction (see Fig. 1a). As a matter of fact, molding—a standard fabrication technique for elastomers—was employed to fabricate the samples, hence the uniformity of the film, and numerical modeling was restricted to 2D simulations due to computational complexity and cost.

A 3D pattern may be obtained in a free-standing *uniform* MRE film bonded to a passive substrate (see Fig. 1b) but, in this case, much larger magnetic fields are required, and the shape of the obtained patterns cannot be finely controlled. The critical fields may be reduced by applying equibiaxial compression or by using an MRE substrate [**Ram21**] but the resulting 3D patterns tend to remain stable only in a very narrow range of mechanical biaxiality beyond which the pattern goes back to the simpler 2.5D wrinkles. **In this project, we aim at overcoming such a limitation to reach controllable targeted 3D patterns in the context of a magnetic field actuation**. This entails going beyond *uniform* MRE layers by endowing them with *heterogeneous* magneto-mechanical properties. Uniformity of the layer is inherently imposed by the molding technique that is commonly used in the fabrication of elastomer structures and, for lifting this barrier, **3D printing** is a very promising avenue that is currently emerging in the field of MREs, and especially in the domain of magneto-induced shape morphing (see, for example, the work of Kim *et al.* [**Kim18**] who printed thin flat origami-inspired sheets with alternated magnetic orientations but uniform particle volume fraction).

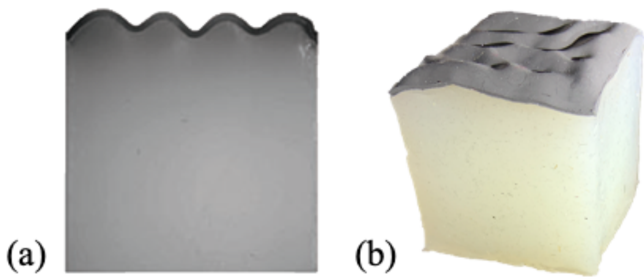

Figure 1. *(a) Controllable 2.5D wrinkling pattern for a uniform MRE film bonded to a non-magnetic substrate submitted to 20% compression and 0.4 T magnetic field. Extracted from [**Psa17**]. (b) Non-controllable 3D pattern for a uniform MRE film bonded to a non-magnetic substrate submitted to 0.8T magnetic field.*

References

[Bod18] L. Bodelot, J.-P. Voropaieff and T. Pössinger. *Experimental investigation of the coupled magneto- mechanical response in magnetorheological elastomers*. Exp. Mech., 2018, 58(2):207–221. DOI: 10.1007/ s11340-017-0334-7

[Kim18] Y. Kim, H. Yuk, R. Zhao, S. A. Chester and X. Zhao. *Printing ferromagnetic domains for untethered fast-transforming soft materials*. Nature, 2018, 558 :274–279. DOI: 10.1038/s41586-018-0185-0

[Psa17] E. Psarra, L. Bodelot and K. Danas. *Two-field surface pattern control via marginally stable magnetorheological elastomers*. Soft Matter, 2017, 13:6576–6584. DOI: 10.1039/C7SM00996H

[Psa19] E. Psarra, L. Bodelot and K. Danas. *Wrinkling to crinkling transitions and curvature localization in a magnetoelastic film bonded to a non-magnetic substrate*. J. Mech. Phys. Solids, 2019, 133:103734. DOI: 10.1016/j.jmps.2019.103734

[Ram21] M. Rambausek and K. Danas. *Bifurcation of magnetorheological film-substrate elastomers subjected to biaxial pre-compression and transverse magnetic fields*. Int. J. Nonlin. Mech., 2021, 128:103608. DOI:10.1016/j.ijnonlinmec.2020.103608

Thesis description

The proposed thesis includes both experimental and numerical aspects.

The experimental goals are to propose:
1) a strategy to 3D print heterogeneously patterned MRE films
2) a protocol for the experimental characterization of magneto-activated 3D patterns by means of stereo digital image correlation

The numerical objectives are to:
1) assess existing models for the magneto-mechanical response of homogeneous MREs
2) extend these models for the magneto-mechanical response of heterogeneous MREs

Practical information

- 3-year position
- Expected start date: May, 1st 2021 - possibly September, 1st 2021 if the interested candidate needs to complete a master's degree internship beforehand, in which case, it would be preferred (but not mandatory) that the internship is conducted at LMS on the proposed subject
- Thesis directors: Laurence Bodelot and Kostas Danas
- Affiliation: Laboratoire de Mécanique des Solides (LMS – Solid Mechanics Laboratory), CNRS
- Location : Ecole Polytechnique, Institut Polytechnique de Paris
  Route de Saclay
  91128 Palaiseau Cedex – France
- Some visits to Stuttgart are expected as part of the collaboration
- Contact: laurence.bodelot@polytechnique.edu

Expected profile

- A Master's degree in Mechanical Engineering or Materials Science and Engineering
- Strong background in experimental work, including attention to detail and capacity to write detailed experimental protocols
- Good background in FE modeling and simulations, especially multiphysics simulations
- Programming skills: Python, C++, Fortran
- Good communication (oral and written) skills in English.