Development of a magneto-mechanical bench and experimental characterization of magneto-rheological elastomers

Maxime Savary[1], Svenja Hermann[1, 2, 3], Christophe Espanet[1], Valentin Préault[1],
Gaël Chevallier[2], Pauline Butaud[2], Jean-François Manceau[3]

[1]Research and Development Department, Moving Magnet Technologies SA, Besançon, France
[2]Applied Mechanics Department, FEMTO-ST, 88524 Besancon, Franche-Comte France
[3]Micro Nano Sciences and Systems, FEMTO-ST, 88524 Besancon, Franche-Comte France

Magneto-rheological elastomers belong to the class of smart materials whose mechanical properties can be controlled by an external magnetic field. These materials can be integrated into mechatronic systems and submitted to multiple loadings such as temperature, mechanical stress and magnetic field. Thus, the present work is dedicated to the development of a magneto-mechanical bench and on first experimental characterizations of hard magneto-rheological elastomers taking multiphysics coupling into account. Regarding the mechanical loading, the experimental setup is able to create a uniaxial tensile stress in case of low strain (< 1%) without friction effect. In regards to the magnetic loading, a magnetic circuit made of a strong permanent magnet has been designed to impose a variable and a homogeneous magnetic field strength up to 41 kA/m. Experimental analysis has been performed on silicone rubber filled with 36%vol. of NdFeB particles. The purpose was first to investigate the evolution of the Young modulus with or without magnetic field. Results obtained from measurements show that the developed test bench is able to depict the mechanical behavior and phenomena linked to rubber-like material.

Index Terms—**Magneto-Rheological Elastomers, Magneto-mechanical coupling, Test bench.**

I. INTRODUCTION

Magneto-rheological elastomers (MREs) are composites consisting of hard or soft magnetic particles embedded in a cross-linked elastomer with various filling ratios. They belong to the class of smart materials whose stiffness and damping can be controlled by an external stimuli as magnetic field. Due to their great flexibility and strain amplitude of the order of 10^{-3} – 10^{-2} under a magnetic field, they can find an interest in the field of mechatronic systems such as soft-robotic or medical technologies [1, 2].

Magneto-mechanical coupling of MREs needs to be clearly understood for the development of mechatronic applications where MREs will be submitted to magnetic and mechanical loadings at the same time. Intense researches have been performed on the magnetic field-induced stiffening effect as well-known magneto-rheological effect (MR effect) [3-5]. This phenomenon is defined as a variation of the Young modulus due to magnetic particles interaction and is strongly correlated to the material's microstructure [3, 4]. The investigation of the MR effect of MREs has been largely studied in the presence and in the absence of an external magnetic field with additional mechanical stress [6-9]. These researches are mainly focused on soft MRE (soft magnetic particles embedded in the elastomeric matrix) and in the case of large strain. The widely test method used consists of a pure shear stress mode [6, 9]. Other modes, as well as tensile stress [6, 8, 9] and compression stress test [6, 7] are less widespread. Regarding the magnetic loading, the use of a pair of strong permanent magnet is not suitable due to non-uniform magnetic field [6]. Other solutions consist of using an electromagnet [7, 8] or a coil [7], but a cooling system is required to limit overheating. The present work deals with the development of an innovative magneto-mechanical test bench and first experimental characterization performed on a hard MRE in the case of low uniaxial strain (<1%) and for a high and homogeneous magnetic field strength. We describe the experimental setup in the next section and then, in section III, we present the first experimental results.

II. EXPERIMENTAL SETUP

An overview of the test rig is presented in Fig. 1. Concerning the mechanical part, the method used consists of a uniaxial tension setup. Due to non-linearities of the mechanical behavior in case of large deformation, strain is limited to a maximum value of 1%. Thus, the challenge is to generate a mechanical loading without friction effect while controlling the stress induced by imposed displacement. The system assembly is composed by a fixed clamp (part 1) and a mobile clamp (part 3) mounted in series with a force sensor (part 6) and a micrometric movable stage (part 5 – compact 5-axis Stage™).

The displacement of mobile clamp, is performed by the micrometric movable platform on which a load cell sensor (part 6 - S100-005™) is fixed by an aluminum holder (part 8). Thus, the beam of the stress controller (part 6), due to its high rigidity (E ~ 200 GPa), is able to impose the displacement of the movable clamp and thus the one of the MRE. An optical position sensor (part 7 - optoNCDT-1420™) has been added into the experimental setup to monitor the displacement of the tested sample from the intermediate stage (part 8). All mechanical parts mentioned are in a POM-C copolymer for parts 2, 3, 6 and 10, in brass for rods assembly (part 9) and in a stainless steel for the force sensor (part 6). The fact that those components are non-magnetic ones helps to improve the magnetic field uniformity in the sample and to reduce the magnetic flux dispersion. Measurement of the displacement (u) and the force (F) are achieved by an oscilloscope. Afterwards, datas are analyzed with using a Python code.

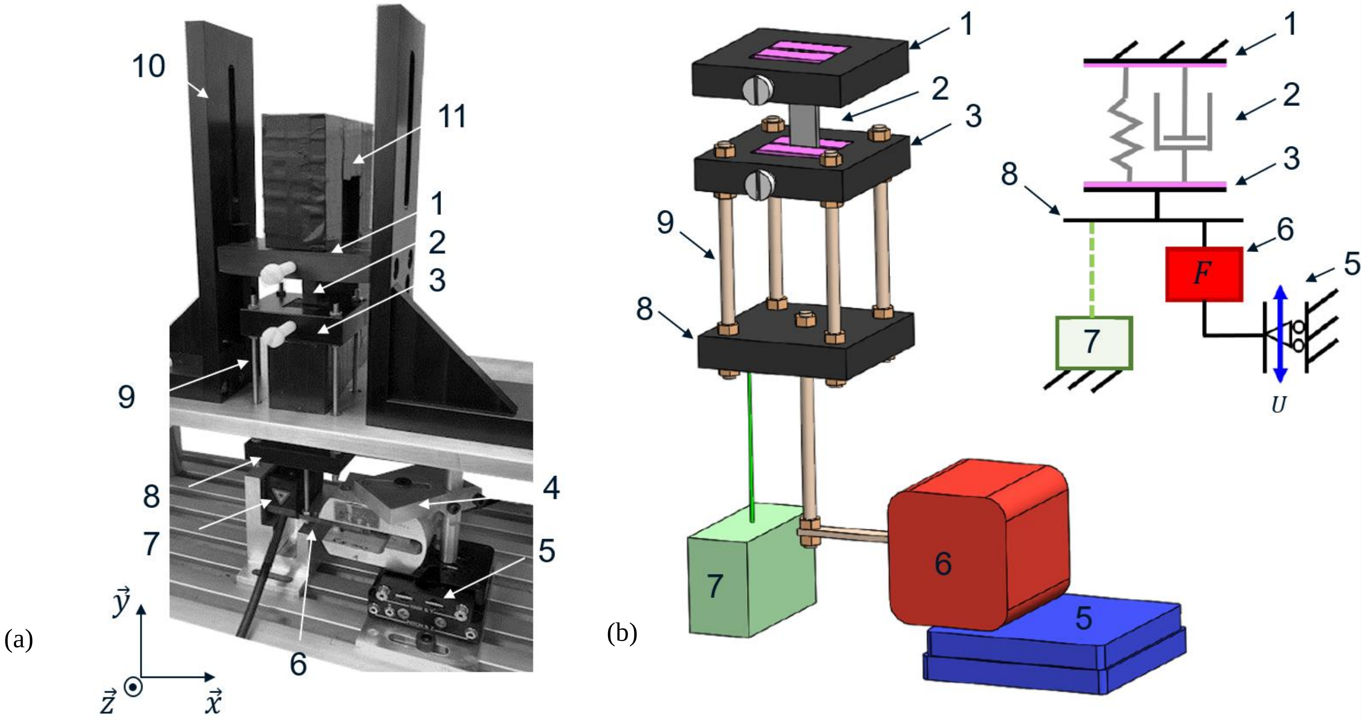


Fig. 1: (a) Overview of the experimental setup; (b) Schematic view of the functional parts of the mechanical loading. 1 – fixed clamp, 2 – MRE sample, 3 – movable clamp, 4 – aluminum holder, 5 – micrometric movable platform, 6 – force sensor, 7 – optical displacement sensor, 8 – intermediate platform, 9 – brass rods, 10 – mechanical frame, 11 – magnetic circuit

Concerning the magnetic part (Fig. 2), loading is performed by a magnetic circuit composed of a static part made of pure iron (part 1) in which a strong permanent Neodymium Iron Boron magnet (B_r = 1.3 T) is enclosed (part 3). To apply a variable magnetic field strength, the strategy consists of a variation of the air gap by the displacement of the movable part (part 2) along the vertical axis. During the magneto-mechanical test, the magnetic field close to the sample can be measured by inserting a Hall effect sensor in the test bench.

The composite, used for the characterization of the magneto-mechanical coupling, is composed of a high consistent silicone rubber (Nusil$^{\text{TM}}$ Med 4014 – $E \sim 10^6$ Pa) mixed by a rolling process with a Neodymium Iron Boron powder (MQFP$^{\text{TM}}$-14-12), provided by Magnequench with a particle size distribution D50 around 5μm. The magneto-mechanical behavior has been characterized for an isotropic MRE with a volumetric filling ratio of 36%. After curing process under a temperature of 116 °C during 10 minutes, samples with a parallelepipedal shape have been magnetized in a strong external magnetic field of 4 T generated by a special magnetization head. Thus, the obtained remanent flux density is 0.3 T and the magnetization direction is along the length of the sample corresponding to the direction of the mechanical and magnetic loadings.

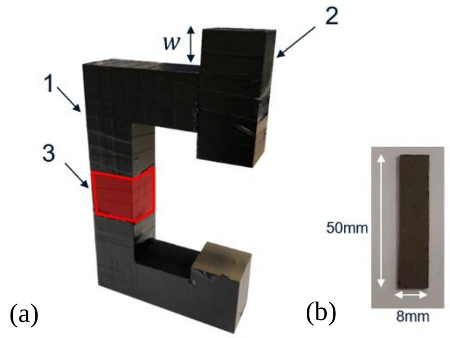


Fig. 2: (a) Magnetic reluctant circuit. 1 – static part, 2- mobile part, 3 – NdFeB permanent magnet; (b) MRE sample

III. EXPERIMENTAL INVESTIGATIONS

A. *Mechanical characterization*

The sample's compression during clamping creates a strained state due to a lateral extension and a buckling of the sample. In order to eliminate this deformation, an initial displacement is imposed to the sample. Mechanical loading is performed step by step using the linear displacement platform. A standby time of 2 minutes is required between step loading to reach a stable state due to stress relaxation. The mechanical quantities such as nominal stress (σ) and nominal strain (ε) have been calculated from datas such as $\sigma = F/S$ and $\varepsilon = u/L_0$ where S and L_0 refer to the cross section area (S = 8 mm^2) and the free length of sample respectively (L_0 = 17 mm).

The results concerning mechanical loading cycles is depicted in Fig. 3 without any external magnetic field. As it can be seen, a hysteretic mechanical behavior is observed with a remanent strain around 0.2% - 0.3%. This effect is well known as Mullins effect with rubber-like materials and corresponds to a cyclic stress softening [10]. Results presented here was also observed for additional tests after demounting and remounting sample in the test rig (Fig. 3b) and for additional specimen. Hence, the setup allows to perform a repeatable and reproductible mechanical loading for MRE samples.

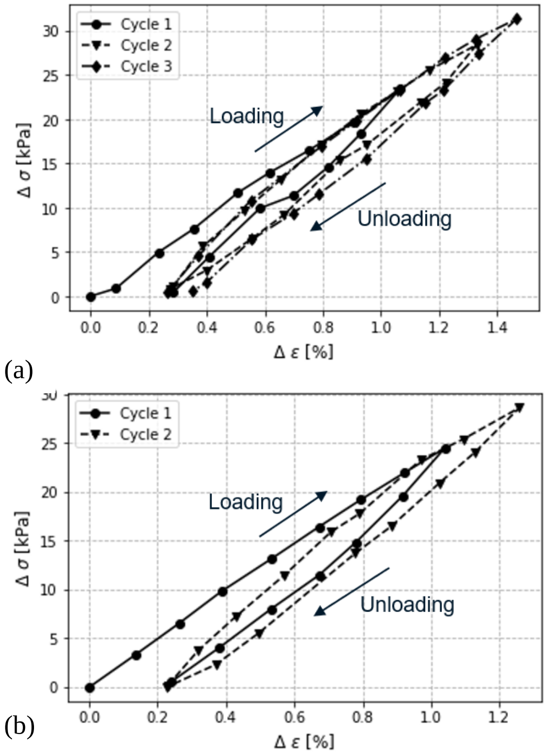


Fig. 3: Mechanical behavior of an MRE filled with 36%vol of NdFeB particles in absence of an external magnetic field for two consecutive mountings of the specimen (a) and (b)

B. *Magnetic characterization*

The magnetic flux density generated from the magnetic circuit in the air gap has been investigated. This measurement consists of the displacement of a Hall effect sensor in the mid-plane of the air gap by using a characterizing tool developed by the company MMT. This characterization has been performed for different air gaps controlled by the length w (Fig. 2). The magnetic field strengths, calculated from the measurement, are between 29 kA/m to 41 kA/m in the central region (Fig. 4). It can be also observed that the magnetic flux density is relatively homogenous in the central area (with an estimated variation around 1.5%) and a non symmetric magnetic field for the outer regions along y-axis due to the proximity of the permanent magnet.

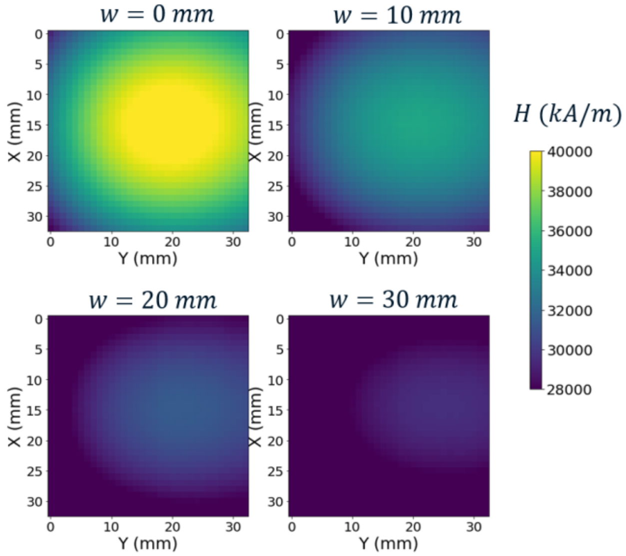


Fig. 4: Cartography of the magnetic field in the mid plane for different air gaps.

C. *Magneto-mechanical characterization*

The first experimental analysis concerning the magneto-mechanical coupling consists of the study of the elastic modulus both with and without an external magnetic field. Displacement and force signals show a strong variation during the time acquisition in which the magnetic circuit (H = 41 kA/m) is added into the setup (from 5 s to 15 s - Fig. 5). Thus, a difference of the force and the displacement of 0.07N and 5µm respectively from the stationary values depicted by green and red dots (Fig. 5) is observed. For a better understanding, the variations of the stress and the strain (respectively $\Delta\sigma$ and $\Delta\varepsilon$) have been compared due to the offset induced by the magnetic field.

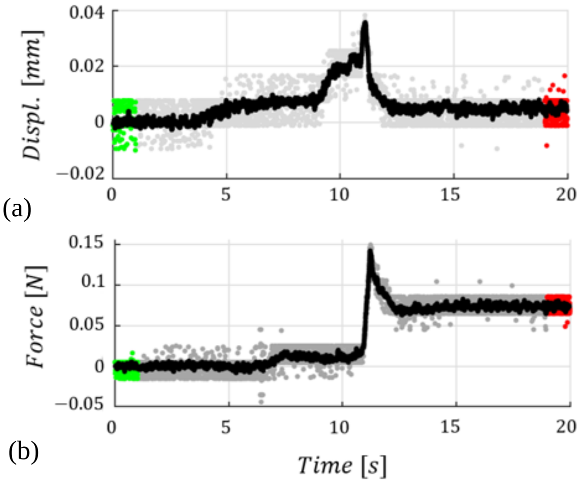
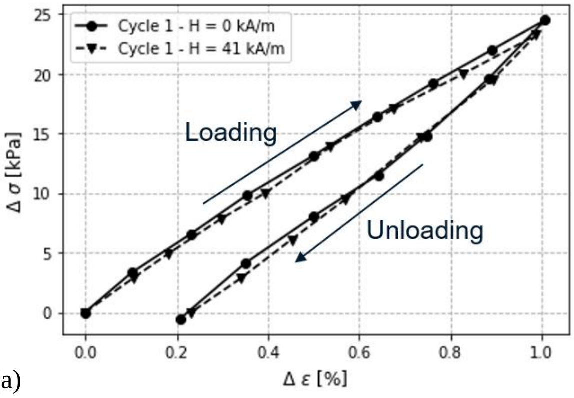
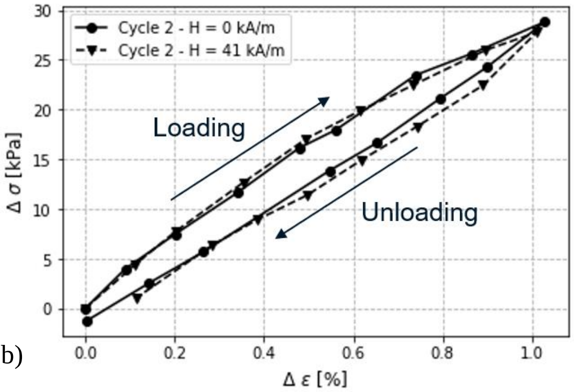


Fig. 5: Evolution of (a) the displacement and (b) the force due to the addition of the magnetic circuit to the setup.

The magneto-mechanical coupling experiments have been conducted only with an external magnetic field of 41 kA/m (w = 0 mm). The direction of the magnetic field and sample's magnetization are oriented toward the same direction. A comparison of the mechanical behavior both in the absence and in the presence of the magnetic field is made for the first cycle loading (Fig. 6a) and the second cycle loading (Fig. 6b). It can be observed that the Young modulus and its standard deviation calculated from slopes between consecutive measurement point (Table 1) are not affected by the magnetic loading. According to Borin et al. [11], a Young modulus of 200 kPa is the limit for a significant MR effect. Thus, due to the high stiffness of the elastomeric matrix used for the experiments (E ~ 10^6 Pa), the magnetic field has no significant influence neither on the particles motion nor on the Young modulus.



(a)



(b)

Fig. 6: Comparison of the mechanical behavior in the presence and in the absence of an external magnetic field (a) first loading cycle; (b) second loading cycle.

TABLE I

COMPARISON OF THE YOUNG MODULUS FOR DIFFERENT MAGNETIC LOADING

Test	E [MPa], cycle 1		E [MPa], cycle 2	
	loading	unloading	loading	unloading
H = 0 kA/m	2.32±0.13	3.13±0.36	2.67±0.55	2.79±0.2
H = 41 kA/m	2.35±0.25	3.00±0.15	2.61±0.53	2.74±0.16

IV. CONCLUSION

Magneto-rheological elastomers exhibit a variation of their stiffness under the application of an external magnetic field due to magnetic particle interaction. A supplementary loading such as a mechanical stress can act on this magneto-rheological effect. This class of smart materials can be integrated into mechatronic systems whose magneto-mechanical properties must be clearly understood.

The present work proposed an innovative characterizing tool for the investigation of the magneto-mechanical coupling in magnetically hard MRE. The setup presented here is composed of an apparatus able to generate a mechanical strain up to 1% without friction effect. In addition, a reluctant circuit has been designed as a magnetic loading. The magnetic circuit is composed of a strong permanent magnet and a movable part which is able to reach a homogenous magnetic field in the sample area between 29kA/m and 41kA/m.

The first experimental characterization has been presented in this work. Uniaxial tension tests were conducted on hard MRE in the presence and in the absence of an external magnetic field. The experimental data have shown the ability of the setup to characterize the mechanical behavior of the magnetic elastomer and common phenomena of cross-link elastomers such as Mullin's effect. The magnetic field had no significant influence on the Young modulus due to the stiffness of the matrix. Thus, these results are very promising for the design of mechatronic application for which magnetic and mechanical loading can be considered separately. Further tests must be performed on softer elastomeric matrices, for different filling ratios and polarization orientation for isotropic and anisotropic MRE to study the influence of these parameters on the magneto-mechanical coupling.

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