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Torque characterization of functional magnetic polymers using torque magnetometry

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ABSTRACT

Magneto-Rheological Elastomers (MREs) are functional magnetic polymers filled with magnetic particles. MREs with fixed magnetic polarization within the particles, or H-MREs, develop a torque in response to an applied magnetic field. This ability leads to unique actuation properties which are critical for designs and applications of flexible actuators employing H-MREs. Thus, the primary goal of this paper is to characterize the relationship between torque generated and volume concentration of magnetic particles, an essential design parameter in H-MRE fabrication. To this end, a torque magnetometer based on a parallel plate capacitor was designed, and used to measure the torque response from H-MRE samples. The H-MRE samples were fabricated with varying percent volume of magnetic particles. The results from torque testing paralleled theoretical trends expected for the samples. An empirical correlation between volume content and maximum torque was found for samples above 10% volume composition and followed a linear trend. The equation governing the relationship was found from experimental results.

1. Introduction

Magneto-Rheological Elastomers (MREs) are emerging smart materials that have the potential for many actuator and sensing applications due to responses in the material from magnetic and mechanical stimuli. These functional magnetic polymers are fabricated by dispersing metallic particles throughout an elastomer matrix. Previous work on MREs has been done to test experimental accuracy of computational models involving MRE systems, and to better describe the response of the material under applied magnetic fields [1,2]. Moreover, most MRE research has focused on “soft” MRE materials. Soft MRE (S-MRE) contain magnetically soft filler materials, such as alloys of iron, to impart magnetic characteristics to the elastic material. These materials have the unique property of field-dependent stiffness. The shear and elastic moduli of the material can be altered with applied magnetic fields; hence, many researchers have used MREs as controllable stiffness elements in various engineering applications, particularly in adaptive vibration absorbers and base-isolation systems [3,4].

Recently, a new type of MRE with hard magnetic particles embedded within the elastomer (H-MREs) has been studied [5,6]. Unlike MREs with magnetically soft filler materials (S-MREs), H-MREs have a fixed net magnetization and are capable of generating torques when an external magnetic field is applied. When the applied field is not parallel to the magnetization, a torque response is observed in a hard magnetic particle as shown in Fig. 1. This behavior of the material is what makes H-MRE materials so promising for actuator applications.

For any actuator, one of the important characteristics is the output response magnitude of the material and in what

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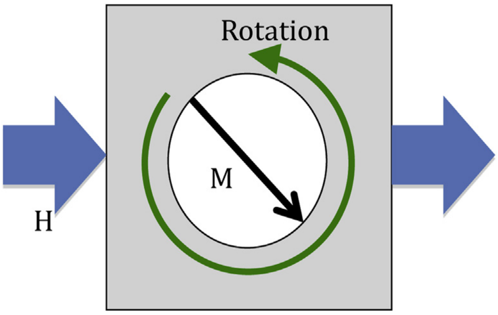

Fig. 1. Torque developed in H-MRE material with net magnetization M as a response to applied field H produces a rotation in the sample. For the example the torque produced would be in the direction coming out of the plane of the image.

conditions it produces the maximum response. These maxima provide boundaries for modeling behavior and determine limits for applications.

One use for H-MRE materials investigated is as a bending actuator. As shown in Fig. 2, a H-MRE material in a cantilevered-beam (fixed-free) configuration results in the displacement of the tip and generates a blocked force at the tip. Responses for the tip force and displacement of different types of H-MRE materials have already been studied and compared for different types of MRE materials. Lofland et al. studied the four types of MRE materials, (aligned and unaligned, soft and hard) and showed the aligned H-MRE materials exhibited the largest force and displacement measurements and is the most suitable candidate for remotely powered actuating applications [5].

In the case of the bending actuator applications of H-MREs, the torque response of aligned individual particles on the micro-scale results in the macroscopic deformation (“rotational” motion about the fixed end) of the MRE material. This deformation produces the blocked force response of the actuator as the composite material reacts to align with the applied field. For designing a bending actuator from H-MRE material, the deformation mechanism of which relies on internal torque, the torque response must first be characterized. With higher volume concentrations, the material exhibits larger torques but loses some of its elasticity. Investigating the microscopic torque response of the material will allow the behavior of various volume concentrations to be modeled and allow for precise fabrication of material to balance actuating application parameters. An accurate measurement is required for the relationship between magnetic particle volume fill percentages and torque response to be developed. A better understanding of this response for H-MRE materials will lead to more accurate design analysis and more innovative applications for the material. Torque magnetometry offers a simple solution to studying these internal torques and can provide information on the maximum torque response as well as the anisotropy of the H-MRE samples.

Torque magnetometry is a frequently used method to characterize the torque response from magnetic samples and provide insight into the magnetic anisotropy of the material [7]. Magnetic anisotropy provides insight into the nature and alignment of the magnetic moments within a H-MRE sample. Hard magnetic materials have high uniaxial anisotropy, holding the particle magnetization in a fixed orientation. The uniaxial anisotropy switching field is typically on the order of several kilogauss. Fig. 3 shows a hysteresis loop of an H-MRE sample used in this study (see Fig. 4). As shown by x-intercepts of the magnetization hysteresis loop in the figure, the switching field is around 2500 gauss.

When a field smaller than the switching field is applied to a hard magnetic sample, the embedded particles will exhibit an effective unidirectional anisotropy as the magnetization remains in its fixed position. Torque applied to a magnetic sample can be described by the well-known cross-product

$$T = \mu_o mV \otimes H = \mu_o mVH \sin(\theta) \tag{1}$$

where T is the torque, μ_0 is the permittivity of free space, m is the magnetization moment per volume of the sample, V is the sample volume, H is the applied field and θ is the angle between the magnetization and applied field vectors. The mechanism behind this relationship stems from the magnetic moments of the particles within the sample trying to align their net magnetization with the applied field.

Some torque magnetometers rely on a torsion rod with a known torsional stiffness and a goniometer or some similar method for taking measurements of sample angular

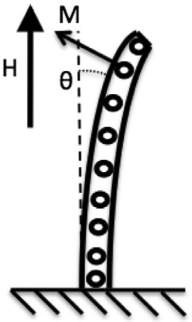

Fig. 2. Cantilever bending for H-MRE bending actuator with perpendicular magnetization direction M, applied field H and deflection θ.

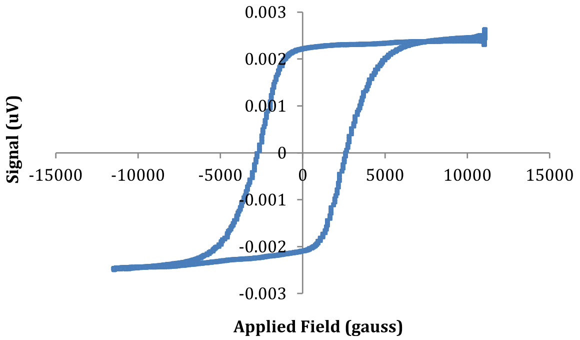

Fig. 3. Hysteresis loop for a Barium Ferrite H-MRE sample. Switching field is shown by x-intercept at around 2500 gauss.