Tuning the tensile modulus of magnetorheological elastomers with magnetically hard powder

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Abstract. It has been experimentally determined the tensile modulus of magnetorheological elastomers based on magnetically hard particles. Samples of the elastomer consisting of a soft elastic matrix and micron-sized particles of FeNdB powder have been magnetized in uniform magnetic fields of varying strength in order to provide different remanence magnetizations. The tensile modulus of these samples was measured small and large strain regimes (up to 6.6%) through mechanical elongation with a table top machine. The relative change in the tensile modulus after the sample was magnetized can reach 360%, depending on the remanence magnetization and the strain.

1. Introduction
The most well-known and controllable property of elastic composites with embedded magnetic particles is the so-called MR effect [1], which is in contrast to magnetorheological fluids an increase in elasticity in an external magnetic field. These composites are usually known as MR or magnetoactive elastomers [2, 3, 4]. As previously shown, if the matrix of the composite is sufficiently soft, i.e. if the elasticity modulus does not exceed 200 kPa, an enhanced MR effect exceeding 1000% will be observed, as will magnetically driven shape memory and giant deformational effects [5, 6, 7]. Common ways to develop an MR elastomer with desirable properties are varying the chemical composition of the elastic matrix [8], controlling the parameters of the curing process, or modifying the powder morphology, size, etc. [9, 10]. The magnetic powder is usually made of carbonyl iron, magnetite, or iron oxide. Once cured, MR elastomers have certain viscoelastic properties which are controllable with an applied magnetic field. However, these properties can only be tuned by means of this external stimulus. We propose using a magnetically hard powder which will enable adjustment and control of the elasticity of soft MR elastomers after they are cured. Some studies on the actuation abilities as well as on the electrical properties of composites filled with SmCo particles have been performed [11]. Experiments on the actuation performances of the composite with magnetically hard filler were conducted in [12]. Recently [13], preliminary investigations on elastomers with embedded FeNdB microparticles have been performed. In the present work, we consider the influence of the remanence magnetization on the tensile modulus of an MR elastomer measured by mechanical elongation. This modulus is important parameter in terms of application point of view.

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2. Sample preparation

The soft matrix of the composite is composed of a low-molecular, vinyl-containing silicon rubber and a hydride-containing cross-linking agent [4]. The FeNdB-powder is a mixture of small (average size \(\sim 4\mu m\)) and large (average size of \(\sim 50\mu m\)) particles which have been mechanically stirred into the liquid polymeric matrix. The overall weight concentration of the powder was \(\sim 80\%\), and the ratio between small and large fractions was 1:4. After the suspension was degassed, it was cast into a mold for further curing at temperatures of about 100\(^\circ\)C. In this way, cylindrical samples with a diameter of 10 mm and a height of 15 mm were prepared. After the cross-linking procedure, the samples were magnetized using the uniform magnetic field provided by an electromagnet (Bruker, Germany), in order to obtain a remanence magnetization. The relationship between the intensity of the external field used and the corresponding remanence was determined with a vibrating sample magnetometer (Lake Shore 7407, USA) and is given in Table 1.

| \(B\) (mT) | 0   | 750 | 1020 | 1500 | 1850 |
|------------|-----|-----|------|------|------|
| \(B_r\) (mT) | 0   | 60  | 83   | 103  | 110  |

3. Experimental

For mechanical testing of the prepared samples, a table-top machine from Dyna-Mess (Germany) was used. The machine is equipped with a force unit with a nominal load capacity up to 5 kN and an efficient servo-pneumatic drive. The class of accuracy for both the load cell and displacement transducer is 0.1, and the best possible resolution for the measurements is 0.01 N and 0.01 mm, respectively.

![Figure 1. Schematic representation of the experimental setup.](image)
necessary to avoid significant influence of the sample deformation in the radial direction on the results of the measurements, since this parameter is not controlled during the experiment. The force-displacement diagrams for samples magnetized in fields of different strengths are shown in Figure 2. With increasing magnetization, larger forces are needed to elongate the elastomer.

The qualitative explanation of this behavior is similar to the one known for the MR effect, which is driven by an external magnetic field in elastomers containing magnetically soft particles. The particles are oriented and aligned in the direction of the acting field. The higher the field intensity is, the higher the mechanical force needed to overcome interparticle interactions and deform the sample. If a sample is magnetized in a field with a flux density higher than \(1500\) mT, no further pronounced changes in the force-displacement dependency can be observed, due to magnetic saturation of the embedded powder.

Figure 2. Force-displacement diagrams obtained from the elongation of the MR elastomer samples magnetized in fields of varying induction \(B\).

To determine the tensile modulus, the measured forces and displacements are transformed into stress and strain values, respectively, taking into account the geometry of the sample. The tensile modulus is defined as the slope of the stress-strain curve, and, as shown in Figure 3, one has to distinguish between the moduli for different strains. Generally, the tensile modulus \(E\) is calculated as \(E=d\sigma/d\epsilon\), where \(\sigma\) is the stress and \(\epsilon\) is the strain, leading to a complex dependence of the modulus \(E\) on mechanical deformation. However, it is sufficient to consider the modulus \(E\) in two major ranges of strain, as illustrated in Figure 3.

The moduli \(E\) obtained this way for small and large strains for samples magnetized in magnetic fields of different flux density \(B\) are shown in Figure 4. The modulus in the small strain regime is significantly higher than that obtained for large strain, as expected. For the higher magnetization fields, saturation is observed. Moreover, the dependence of \(E\) on the field intensity is similar to other properties of magnetoactive materials [1, 2].

To evaluate the quantitative influence of magnetization on the elasticity of the MR elastomer, the relative change in the tensile modulus is calculated as \(R = E(B_r)/E_0 - 1\), where \(E_0\) is the tensile modulus of a non-magnetized sample. The parameter \(R\), given in Table 2 for various remanence magnetizations \(B_r\), can be conventionally designated as a passive MR effect.
Table 2. The relative change of the tensile modulus ($R$) of the MR elastomer for different remanence magnetizations $B_r$.

| $B_r$ (mT) | 60  | 83  | 103 | 110 |
|------------|-----|-----|-----|-----|
| $R$, small strain (%) | 178 | 304 | 354 | 359 |
| $R$, large strain (%)  | 81  | 133 | 182 | 178 |

4. Summary and outlook
It has been shown that the use of a magnetically hard powder allows tuning of the tensile modulus of an MR elastomer by means of remanence magnetization. The relative change of the tensile modulus for small and large strain is shown in Figure 3 and Figure 4.

**Figure 3.** Stress-strain dependence recalculated from the data presented in Figure 2 for the sample magnetized in a field with an induction of 1020 mT. The linear approximations are given to illustrate the difference between the tensile moduli at small and large strains.

**Figure 4.** Tensile moduli of the MR elastomer determined for small and large strain versus induction of the magnetic field used for sample magnetization.
the tensile moduli for magnetized samples can reach up to 360%, depending on the remanence magnetization and on the deformation regime considered. Moreover, the same setup allows to perform a compression testing and corresponding results will be published elsewhere. Further investigations will be devoted to actively controlling this materials properties, as well as to dynamic characterization. Moreover, the basic question of the correlation between observed material performance and microstructural changes will have to be considered for a detailed understanding of the MR effects observed.

Acknowledgments
This project is funded by the European Union and the Free State of Saxony. G.S. is grateful for the financial support of the Federal Agency for Science and Education of the Russian Federation.

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