Characterization of the dynamic mechanical behavior of magneto - elastomers

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Abstract. Due to their magnetic field dependent mechanical response, polymeric materials filled with magnetic particles have become of major practical and theoretical interest. the dynamic-mechanical behavior of polydimethylsiloxane rubber filled with ferro-oxide with and without magnetic field has been investigated in this study. Specimens with different hardness and with two distinct orientations of the fillers (isotropy, anisotropy) were prepared. Dynamic mechanical analysis experiments were performed to determine the storage and loss modulus over a wide amplitude and frequency range with and without external magnetic field. In order to characterize the influence of the ferro-oxide filler particles, a permanent magnetic field to the specimen grips has been attached. The complex-, storage- and loss modulus and the loss factor values were determined. Finally, to compare the isotropic and anisotropic materials a magnetic stiffening factor (MSF) was defined and applied.

1. Introduction and Objectives
The new generation of magnetic gels and elastomers represent novel type of composites, consisting of small (from nano-to-micro sized) magnetic particles dispersed in highly elastic polymeric matrix. To support both material development efforts and engineering design and applications, it is of prime theoretical and practical importance to characterize the complex magneto-dynamic mechanical behavior of elastomeric materials filled by magnetic particles [1,2,5]. Hence, the objectives of this study were: (1) to implement a permanent magnet for an electrodynamic test system and (2) to characterize the complex dynamic mechanical/magnetic behavior of isotropic and anisotropic magnetic particle filled elastomers.

2. Experimental

2.1. Materials and Specimens
Polydimethylsiloxane rubber (PDMS) materials filled with magnetic particles (Fe₃O₄) were prepared in 4 different hardness degrees by varying the curing additive (from 3 to 4.5 wt%) and with two
distinct distributions of the filler particles (isotropic and anisotropic) as is shown schematically in figure 1.

![Figure 1. Isotropic and anisotropic distribution of the particles](image)

![Figure 2. Fe₃O₄ particles](image)

Fig 2 shows the particle used with an average diameter of approximately 8.4µm. Cylindrical specimens with diameter of 25mm and heights of 4, 6 and 25mm were prepared with and without the application of magnetic field. The cubic specimens with 18 mm edge length were only prepared in magnetic field. The curing process in magnetic field results in a highly anisotropic particle distribution. For more details about the materials and the preparation technique please refer to [3].

2.2. Testing Machines, Test Methods
Dynamic mechanical analysis (DMA) tests were performed using novel electro-dynamical testing machines (BOSE 3100 and 3450 BOSE Corp. MN, USA) in the small-scale deformation regime. All experiments were conducted in compression mode, with and without the application of magnetic field.

2.3. Measurement of the Magnetic Field
To characterize the deformation behavior in magnetic field, a permanent magnet with the nominal magnetic field of about 0.44 Tesla was placed under the specimens. To determine the distance dependence of the magnetic field of the permanent magnet and hence the inhomogenity of the field acting on the particles in the specimen, a calibration curve with a Hall-sensor was first measured and the results are plotted in figure 3. As expected a significant decrease of the magnetic field as function of distance was observed.

![Figure 3. Magnetic field of permanent magnet in dependence of displacement](image)

3. Results
3.1. Amplitude behavior
To characterize the deformation behavior of magneto-elastomers, cyclic tests were performed over a wide deformation amplitude range. All tests were performed at a mean level of 0.5mm in compression at 8 different dynamic amplitudes ranging from 0.02 to 0.8mm and at a constant frequency of 1Hz. The hysteretic deformation behavior of the anisotropic and isotropic specimens with 3 wt% curing
additive is shown in figure 4 at the same test amplitude. While a linear behavior of the isotropic specimen with small hysteresis was observed, the anisotropic specimen reveals a highly non-linear behavior and significantly higher hysteresis [4].

3.2. Frequency behavior
Dynamic mechanical analysis tests were performed over the frequency range from 0.1 to 100 Hz at a dynamic amplitude of 0.2 mm. The dynamic, $E^*$, the storage and loss modulus, $E'$, $E''$ and tanδ values were determined for all experiments. The frequency dependence of the storage modulus $E'$ for a 3.5 wt% cubic specimen with loading perpendicular and normal to the particle orientation is shown in figure 5 without magnetic field. The filled symbols represent the results without magnetic field. A clear increase of the storage modulus was observed for both loading directions.

3.3. Influence of the magnetic field
Furthermore, the frequency dependence of the modulus was also investigated in magnetic field. As it was emphasized before, the permanent magnet produces an inhomogeneous magnetic field, that is, the particles have different magnetic forces as a function of the specimen height in the specimens. In spite of this fact, the increase of the modulus up to about 20% was observed in compare to the test without magnetic field as it is depicted in figure 5. This increase of the modulus was found highly depends on the magnetic particle distribution (iso or anisotropic) and on the hardness (3 to 4.5 wt% curing additive results in about 100% change of the hardness) of the specimens.

3.4. Influence of the load direction combined with magnetic field
While a clear difference between the deformation behavior of the material for various load directions relative to the particle orientation was observed for the anisotropic specimens, the isotropic specimens revealed similar response. A difference in perpendicular loading direction between loading with and without magnetic field intensity could not be observed. Moreover, magnetic field intensity affects on harder material higher than on softer.
3.5. Magnetic Stiffening Factor

The magnetic stiffening factor was defined, which characterizes the ratio between the results with and without of magnetic field.

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MSF = \frac{E_{MF}}{E_0}
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The frequency dependence of the magnetic stiffening factor for isotropic particle distribution is shown in figure 6a. As clearly depicted in this figure, isotropic specimens independent from the hardness degree revealed the same MSF values over the frequency range investigated. The frequency dependence of MSF is shown in figure 6b for anisotropic specimens. For anisotropic particle distribution higher magnetic stiffening factor was observed (20 to 35%). Furthermore, no clear tendency was found for the variation of the amount of curing additive.

![Figure 6: Magnetic stiffening factor for (a) isotropic and (b) anisotropic particle orientation](image)

4. Conclusions

Based on the experimental results described above some general conclusions may be drawn:

- Clear differences of the hysteretic behavior between isotropic and anisotropic specimens were observed.
- Magnetic particle filled elastomers revealed a similar frequency and amplitude dependent behavior with and without magnetic field.
- The combination of the mechanical loading direction, the magnetic field direction and the particle orientation was found clearly influence of the dynamic mechanical behavior of the cubic specimens.

In comparison to the conventional dynamic mechanical analysis, the additional application of magnetic field and the application of anisotropic specimens clearly increase the complexity of the tests and hence the characterization of the material behavior. However, to support practical engineering applications of magneto-elastomers, the determination of the influence of all parameter combinations (mechanical loading, frequency, material anisotropy, magnetic field) on the material behavior is necessary.

References

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