JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 15, No.3 - 4, March – April 2013, p. 249 - 253

Oscillation measurements on magnetoactive elastomers with complex composition

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Rheological properties of magnetoactive elastomers with complex composition are studied. Samples of the elastomer consisting of a soft silicon matrix with embedded micron-sized particles of FeNdB and carbonyl iron powder have been magnetized in the uniform magnetic field of varying strength in order to provide different remanence magnetizations. The storage and loss modulus of samples with different geometries have been measured using oscillating rheometry. The possibility of the passive tuning as well as an active control of the rheological properties of prepared elastomers is shown.

(Received February 1, 2013; accepted April 11, 2013)

Keywords: Magnetorheological elastomer, Magnetic hard, Rheology, Torsion oscillation, Storage and loss modulus

1. Introduction

Magnetoactive elastomer (MAE) is a promising material for the vibroisolation and damping [1,2], like conventional magnetorheological (MR) materials [3]. It has also very high innovative potential in the sensoric and actuation applications [4]. MAE basically consists of two components, which are elastic matrix and magnetic powder. Therefore, physical properties of the MAE can be rapidly and reversibly controlled with an external magnetic field.

Common way to develop a MAE with desirable properties is varying the chemical composition of the matrix [5] or applying the magnetic field during the curing in order to obtain the structural anisotropy in the direction of the applied field [6]. The control of the curing process and modification of the powder morphology, size, etc [7] can be used to tune the parameters of the MAE. However, regardless to the temperature influence, it is not possible to change off-state physical properties of the MAE after the matrix has been polymerized. A possibility of the passive tuning of the MAE properties is very promising in regards to the technical applications. It can be reached using magnetically hard particles as a powder [8, 9]. In this paper we report on rheological properties of the MAE with complex composition. The powder of the studied samples is a mixture of magnetically hard particles and carbonyl iron. Samples of the cured MAE have been magnetized in the uniform magnetic field in order to obtain a remanence magnetization. We used two different experimental procedures to prove if the geometry of the samples can has an influence on measured material properties. Disc-shape samples were used in the conventional shear oscillation examination and cylindrical samples were used in the torsion dynamic test.

2. Experimental

2.1 Sample preparation

The soft matrix of the composite is a silicon rubber in which spherical particles of FeNdB-powder (Magnequench MQP™-S-11-9, average diameter ~50μm) and carbonyl iron powder (CC BASF, average diameter ~5μm) are mechanically stirred. The overall weight concentration of the powder is ~80%, and the ratio between FeNdB and carbonyl iron fractions is 7:1. In figure 1 particles of powder used for the MAE are presented.

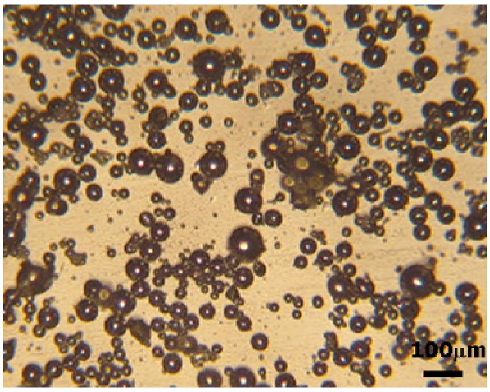

Fig. 1. Optical image of the particles of the powder obtained using metallurgical microscope Euromex ME.2660 and CCD camera.

After the mixture of the liquid silicon and powder was degassed, it has been cast into two kinds of molds for further curing at temperatures of about 100^{o}C. In this way disc-shaped samples (figure 2) with a diameter of 25 mm and height of 5 mm. as well as cylindrical samples (Fig. 3) with a diameter of 5 mm and a length of 65 mm were prepared. These kinds of samples geometry are needed for independent measurements utilizing different methods as described below.

Cured MAE samples have been magnetized using the uniform magnetic field provided by the vibrating sample magnetometer Lake Shore 7407. The different shape of the samples leads to the different demagnetizing field and to the different effective magnetization consequently. However, magnetic investigations have not been conducted in the frame of this study.

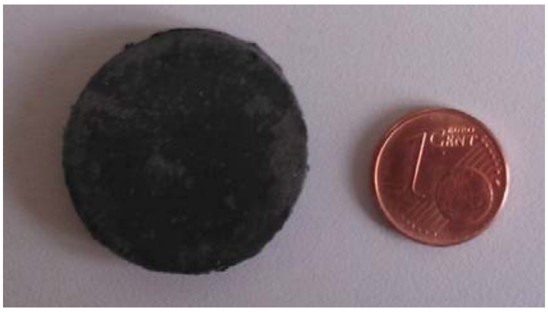

Fig. 2. Disc-shaped sample of MAE for the shear test.

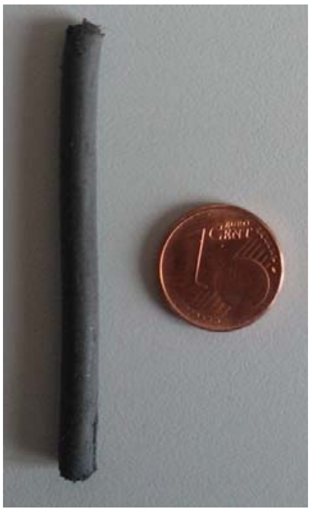

Fig. 3. Cylindrical sample of MAE for the torsion test.

2.2 Setup

For rheological characterization of the samples the rotational rheometer Anton Paar Physica MCR301 was used. The rheometer allowed studying the viscoelastic properties of MAEs in the oscillating mode using amplitude and frequency sweeps.

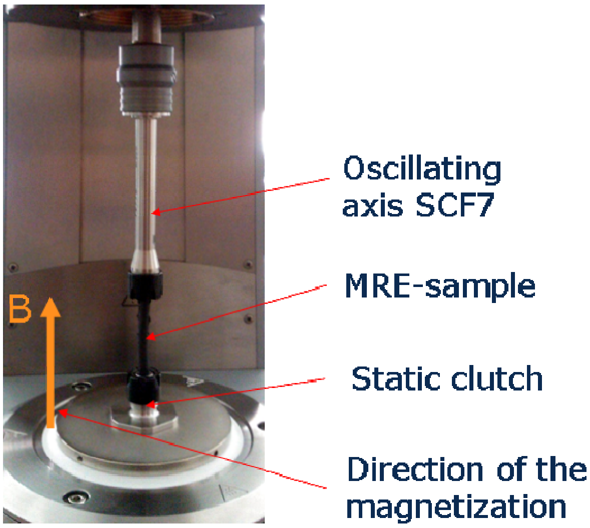

Fig. 4. Setup for the torsion oscillating test (without electromagnetic coil).

Shear test was performed utilizing plate-plate geometry with oscillating axis PP20. The upper plate of the geometry is grooved to ensure the no-slip condition. Control of the normal force ensures the same preloading condition of the sample during the measurements. The normal force at the upper plate was constant at the level of ~2N in all tests. Disadvantage of the used plate-plate geometry is in the impossibility to apply an external magnetic field to disc shaped MAEs. Commercial magnetorheological cell from Anton Paar utilizes working gap of 1 mm, however, magnetized MAE with magnetically hard filler of such thickness will be folded, due to remanence magnetization. Thus, MAE samples with a height of 5 mm were characterized with this method.

In the torsion test the MAE sample is fixed in the rotational axis SCF7 for the solid cylinders from the one side and in the fixed plate of the Peltier tempered device P-PTD200/80/I from other side, as it is shown in figure 4. This arrangement allows using a simple cylindrical electromagnetic coil to generate an external magnetic field in the axial direction. In contrast to the shear test amplitude of the applied deformation in the torsion loading is limited by ~1% to avoid a twisting of the sample. Furthermore, an identical deformation of the sample during the fastening cannot be assured.

2.3 Shear oscillation

Results of shear examinations at the frequency of 1 Hz are presented in figures 5 and 6 for the storage and loss modulus respectively. An increase of the shear amplitude results in the decrease of moduli, similar as it was observed for the common MAE [8].

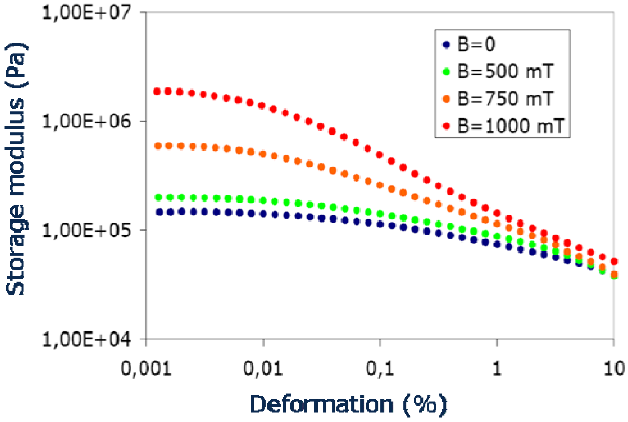

Fig. 5. Storage modulus of the MAE samples magnetized in fields of varying induction B measured within amplitude sweep at the frequency of 1 Hz with plate-plate geometry.

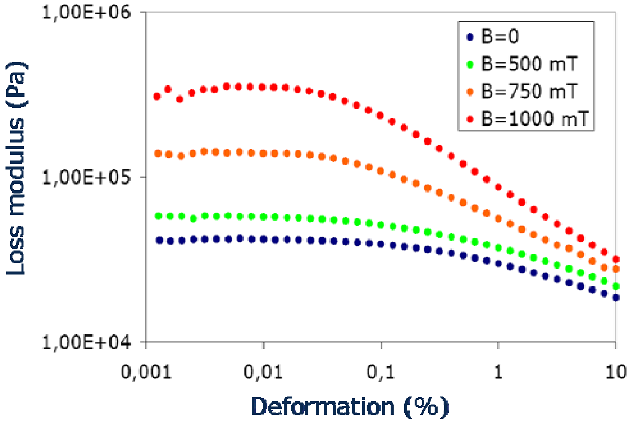

Fig. 6. Loss modulus of the MAE samples magnetized in fields of varying induction B measured within amplitude sweep at the frequency of 1 Hz with plate-plate geometry.

The magnetic particles are oriented in the direction of the magnetization. The higher magnetization is, the higher mechanical force is needed to overcome particles interaction and to deform the sample. Observed dependence of the shear modulus on the amplitude of mechanical deformation is not linear. However, for the estimation of the MR-effect it is sufficient to consider the modulus in two ranges of the strain amplitude.

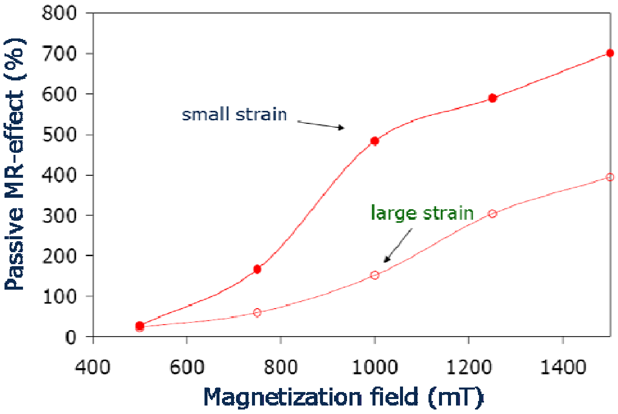

Fig. 7. The relative change of the storage modulus (passive MR-effect) of the MAE magnetized in fields of varying induction B measured with plate-plate geometry at the frequency of 1 Hz.

To evaluate the quantitative influence of the magnetization on the elasticity of the MAE the relative change of the tensile modulus is calculated as $R=G(B_r)/G_0-1$, where G_0 is the storage modulus of a non-magnetized sample. The parameter R can be conventionally designated as a passive MR-effect and its dependence on the fields of varying induction B used for the MAE magnetization is shown in figure 7. As expected the modulus in the small strain regime is significantly higher than that obtained for large strain. The saturation is observed for the higher magnetization. Moreover, the dependence of MR-effect on the field intensity is similar to other properties of magnetoactive materials [1-3].

2.4 Torsion oscillation

Results of the torsion oscillation show qualitatively similar dependence of the storage modulus on the deformation to behaviour obtained at the shear oscillation (figure 8). Distinctive feature is extended range of the linear viscoelastic behaviour observed in the torsion test. Moreover, torsion modulus of the non-magnetized sample is smaller as shear modulus, while it is inversely for the magnetized MAE. Comparison of the passive MR-effect obtained using torsion test with results of the shear oscillation is presented in figure 9. Relative change of the torsion modulus can reaches more than 1200% if sample was magnetized in the field of 1000 mT, while for the shear modulus this change is about 500%. Thus, different samples geometry and test procedure lead to the different results.

However, a correction for the demagnetizing field should be done, since MAEs have the different shapes. This correction was not taken into account when presenting the data. Magnetization of the MAE for the torsion test in the magnetic field with the intensity higher than 1000 mT was not possible, due to the length of the cylindrical samples. Nevertheless, it is to be expected that further magnetization will lead to the saturation of the MR-effect, due to the conventional magnetic saturation of the filler particles, like it is obtained from the shear test.

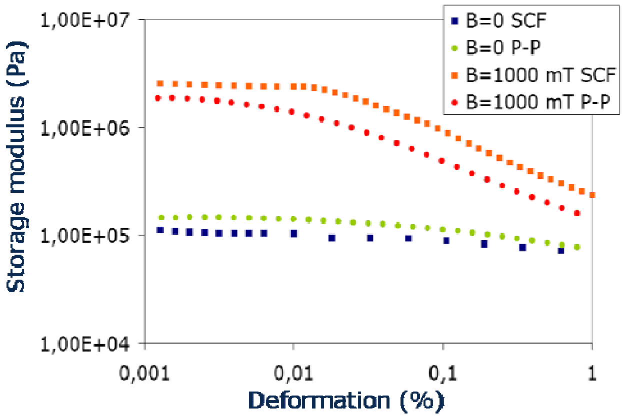

Fig. 8. Comparison of the storage modulus of the MAE samples magnetized in the field B measured within amplitude sweep at the frequency of 1 Hz with plate-plate (P-P) geometry and torsion setup (SCF).

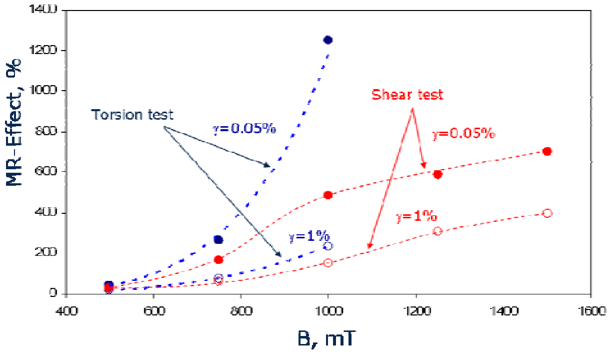

Fig. 9. The relative change of the storage modulus (passive MR-effect) of the MAE magnetized in fields of varying induction B measured within shear and torsion test at the frequency of 1 Hz.

In contrast to the shear oscillation using plate-plate geometry, torsion setup allows to apply an external magnetic field in the axial direction. In this way active control of the MAE could be performed. We have studied influence of the applied field on the storage modulus of the MAE magnetized in fields of varying induction. Fig. 10 shows results of amplitude sweep obtained from torsion test for the non-magnetized sample at the frequency of 1 Hz. External magnetic field allows to significantly change the modulus.

Qualitatively, observed behavior is similar for all used strengths of the magnetic field. The modulus decreases with increasing deformation's amplitude. Use of the magnetic field with a flux density higher than 150 mT can lead to the change of the off-state magnetization, i.e. remanence can be modified. The range of the controllable properties will be constricted if MAE was magnetized beforehand (figure 11). The reason of it is in the remanence and in the already occurred structural changes, which limit further influence of the magnetic field.

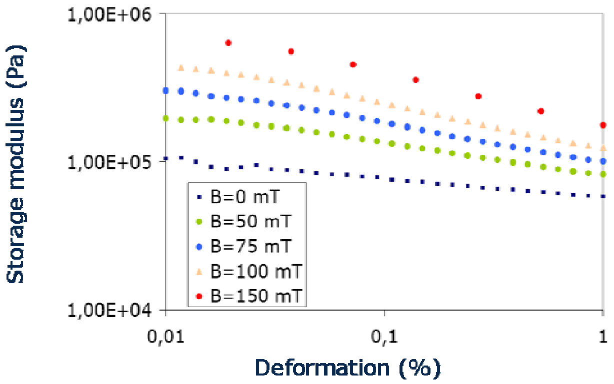

Fig. 10. Storage modulus of the non-magnetized MAE samples under action of the external fields of varying induction B applied during the amplitude sweep at the frequency of 1 Hz performed with torsion setup.

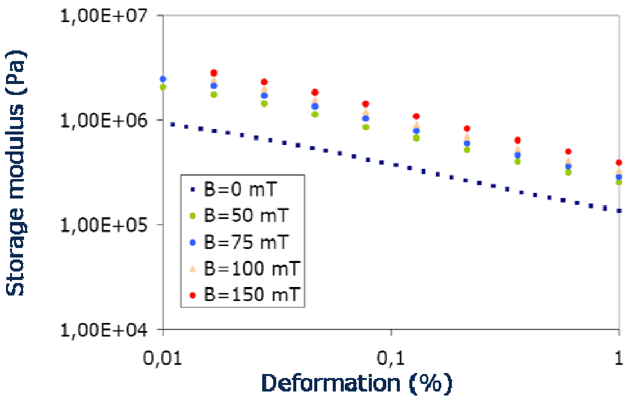

Fig. 11. Storage modulus of the MAE samples magnetized in the field with B=1000 mT under action of the external fields of varying induction B applied during the amplitude sweep performed with torsion setup.

Fig. 12 shows an active MR-effect of the magnetized and non-magnetized MAE as a function of the flux density of the external magnetic field. Similar to the passive effect, the observed behavior is typical for the conventional MR materials.

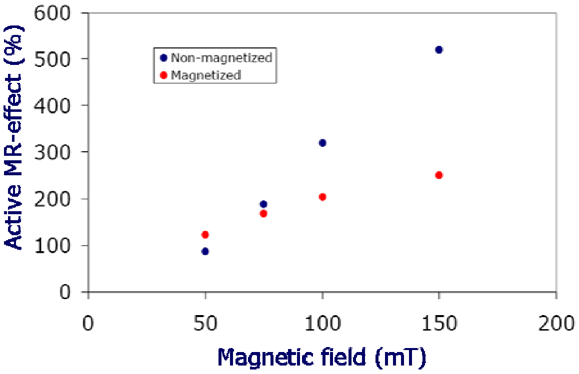

Fig. 12. The relative change of the storage modulus (active MR-effect) of the magnetized and non-magnetized MAE as a function of the external fields applied during the amplitude sweep performed with torsion setup.

3. Summary and outlook

Use of a complex powder allows tuning of the modulus of MAE by means of remanence magnetization. The relative change of the modulus for beforehand magnetized samples can reach up to 1200%, depending on the remanence and deformation regime considered. Used experimental method has a significant influence on the obtained results, which is obviously associated with samples geometry. Magnetic investigation in order to obtain an influence of the demagnetizing field on the effective magnetization of the MAE with different geometries should be done.

Furthermore it was possible to control mechanical properties of MAE actively as it is shown within torsion test. Active MR-effect can reaches up to several hundred percents, showing high application potential of the MAE with complex powder. However, active control is restricted with a flux density not exceeding of 150 mT, to prevent a change of the off-state properties, due to the possible remanence modifications.

Only hypothetical explanation of the observed behavior is possible without insight into the field depended structural changes in the MAE. Thus, an important problem of the correlation between observed material performance and its microstructure should be addressed in further investigation.

Acknowledgments

The financial support of the Federal Agency for Science and Education of the Russian Federation is gratefully acknowledged.

The paper contains results presented at the International Summer School and Workshop Complex and Magnetic Soft Matter Systems: Physico-Mechanical Properties and Structure, CMSMS 12, 3-7 September 2012, Alushta, Ukraine (http://cmsms.jinr.ru/).

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