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Mechanical properties of magnetorheological elastomers under shear deformation

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ABSTRACT

In this paper, urethane magnetorheological elastomers (MREs) consisting of carbonyl-iron particles in a polyurethane matrix were studied. The volume fraction of particles was equal to 11.5%. Three types of ferromagnetic particles were used, with average particle size ranging from 1 to 70 μm. The elastic (storage) modulus G' was measured as a function of angular frequency ω and strength of magnetic field. The measured G' values were approximated with empirical model. The highest magnetorheological effect has been found for samples with 6–9 μm carbonyl-iron powder. The highest increase in the yield stress is observed for samples with particles aligned at 30° to the magnetic field lines. It has been found that rheological properties strongly depend on the MRE microstructure, in particular on the size/shape of particles and their arrangement. By optimizing the particles size, shape and alignment, the stiffness of MREs has been increased under applied magnetic field.

1. Introduction

Magnetorheological elastomers (MREs) are considered as smart materials. They offer variable stiffness and can be used in adaptive structures of aerospace, automotive, civil and electrical engineering applications [1,2] for motion and vibration control.

Magnetorheological elastomers exhibit promising mechanical properties. These materials change their rheological properties depending on external magnetic field. They are similar to magnetorheological fluids, but are their solid equivalents. In magnetorheological elastomers magnetoactive particles (e.g. iron, cobalt) are embedded within elastic polymer matrix [3]. The matrix enables relatively high strains and maintains shape of the element. The magnetorheological effect is based on dipole interactions between ferromagnetic particles [4]. Under a magnetic field, particles tend to align themselves parallel to the magnetic field lines [5]. This tendency has been used to obtain several magnetorheological elastomers with aligned chain-like microstructures. The elastomeric matrix preserves the alignment of particles after a curing process. From our previous research [6] it is known that aligned microstructure gives significantly greater magnetorheological effect than isotropic particle arrangement in MR composites [7,8].

In our work several magnetorheological elastomers were tested under different magnetic field strengths. The tested samples had different arrangement of particles relative to the magnetic field lines. Three types of particles were used, as described in the next section.

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2. Materials and methods

Soft polyurethane (PU) has been used as the matrix of the magnetorheological elastomers. Polyether polyols VORALUX® HF 505 and 14922 (in weight proportions of polyols HF 505 to 14922 equal to 70:30) as the mixture with isocyanate compound HB 6013, supplied by Dow Chemical Company, were used as substrates for PU synthesis. Mixing of the substrates and curing process were conducted at room temperature. PU 70/30 polyurethane is characterized by low density (1.03 g/cm^3), low viscosity before curing (ca. 1600 mPa·s), low hardness (below 10°ShA) and low Young's modulus (below 0.1 MPa). These properties allow to obtain high magnetorheological effect in the composites based on such a matrix. Relatively low viscosity during the processing of the MRE makes alignment of the particles under the external magnetic field relatively easy to obtain.

Three types of ferromagnetic particles were used for production of the MREs. The amount of the carbonyl iron particles was equal to 11.5 vol.%. In previous studies [9] we have obtained the highest magnetorheological effect for this amount of particles. The samples were subjected to a magnetic field during curing reaction in order to obtain aligned iron particle chains within the elastomer. Magnetic field strength of 300 mT has been used. Samples with particle chains aligned or slopped at different angles to the long sample axis were produced.

2.1. Particles

Carbonyl-iron powder, produced by Fluka has been used for fabrication of the samples. It has a spherical shape and average

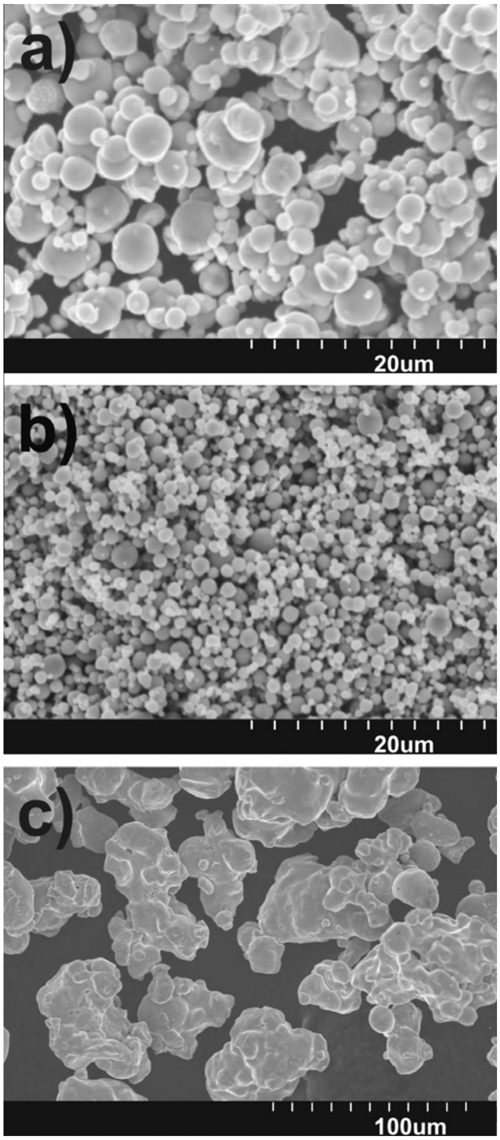

Fig. 1. SEM images of particles used for MRE: (a) carbonyl-iron 6–9 μm by Fluka, (b) carbonyl-iron HQ 1–2 μm by BASF, and (c) iron powder 70 μm by PYRON.

diameter 6–9 μm. Two other powders used were carbonyl-iron powder HQ with particles diameter ranging from 1 to 2 μm, produced by BASF, and iron powder with average particles diameter 70 μm, by PYRON. The PYRON iron has irregular shape. Micrographs of the particles used are shown in Fig. 1.

2.2. Samples

Several types of samples have been produced. Samples for rheological measurements were in the form of circular slices 2 mm thick and 20 mm in diameter. The volume fraction of particles in all samples was equal to 11.5%. Some samples with carbonyl-iron were subjected to magnetic field during curing. The field was applied at different angles to their axis, in order to obtain different particles alignment. Schematic representations of the alignment obtained are shown in Fig. 2. Also, samples with randomly (isotropic) dispersed particles were produced.

Samples with different particles were manufactured under the same magnetic field conditions in order to estimate the influence of particles size/shape on mechanical properties. An example of a typical microstructure of aligned particles is shown in Fig. 3. Table 1 contains a list of manufactured samples.

2.3. Rheometer

Rheological measurements were carried out using ARES rheometer from TA Instruments with variable magnetic field. Plate-plate system with diameters of 20 mm and with a 2 mm gap between plates was used. The magnetic field was varied within 0–600 mT range. Experiments were conducted at ambient temperature of 25 °C.

3. Results and discussion

3.1. Rheological measurements

MR elastomers are normally operated with small deformations in the pre-yield regime of the linear viscoelastic region. The MREs are intended to be used as structural materials in applications where the load is often of a dynamic kind. In cyclic dynamic loading, the material deforms and returns back to its original form during one cycle. The excitation force is varied sinusoidal with the angular frequency ω and has a constant amplitude.

In viscoelastic materials, some part of the deformation energy input is stored and recovered during each cycle and some is dissipated as heat. The storage modulus, G' represents the ability of the viscoelastic material to store the energy of deformation, which contributes to the material stiffness. The loss modulus, G'' represents the ability of the material to dissipate the energy of deformation.

In this study, the elastic (storage) modulus G' has been measured as a function of an angular frequency ω and strength of the magnetic field at the room temperature.

As it is shown in Fig. 4, the storage modulus increases significantly with the increase of the strength of magnetic field. However, this relation is not linear as at higher magnetic fields maximum magnetic saturation of particles is reached and further rise in the value of modulus is negligible, as illustrated by small differences between the curves for 400 and 600 mT. The change of modulus under magnetic field is called the magnetorheological effect. This effect can be used for variable stiffness devices, as it is fully reversible.

Fig. 5 comprises the results for samples with different microstructures at 0 and 200 mT. For all samples the increase in the storage modulus under magnetic field is observed. However, this increase strongly depends on the particles arrangement within the matrix. Samples with particles aligned perpendicular (90°) to the magnetic field and with isotropic distribution exhibit relatively small rise in G'. Higher increase is observed for sample with parallel alignment (0°) and the highest for that with particle chains deflected at 45° and 30°.

This effect is related to the tendency of the composites to attain the minimal energy. Particle chains tend to deflect in direction parallel to the magnetic field lines. Soft matrix enables some elastic displacement of the particles. However such displacement strains the matrix and generates stresses. As a result, material properties are changed. To illustrate these changes an empirical model was proposed.

3.2. Approximation of rheological measurements with empirical model

Rheological behavior of samples fabricated in this study is not fitting to a linear model. We tested different models of viscoelastic materials in order to describe experimental results for storage modulus measurements basing on [10]. The results of rheological