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Research articles

Dynamic response of a sensor element made of magnetic hybrid elastomer with controllable properties

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Smart materials like magnetic hybrid elastomers (MHEs) are based on an elastic composite with a complex hybrid filler of magnetically hard and soft particles. Due to their unique magnetic field depending characteristics, these elastomers offer great potential for designing sensor systems with a complex adaptive behaviour and operating sensitivity. The present paper deals with investigations of the material properties and motion behaviour displayed by synthesised MHE beams in the presence of a uniform magnetic field. The distribution and structure formation of the magnetic components inside the elastic matrix depending on the manufacturing conditions are examined. The specific magnetic features of the MHE material during the magnetising process are revealed. Experimental investigations of the in-plane free vibrational behaviour displayed by the MHE beams with the fixed-free end conditions are performed for various magnitudes of an imposed uniform magnetic field. For the samples pre-magnetised along the length axis, it is demonstrated that the deflection of the beam can be identified unambiguously by magnetic field distortion measurements. It is shown that the material properties of the vibrating MHE element can be specifically adjusted by means of an external magnetic field control. The dependence of the first eigenfrequency of free bending vibrations of the MHE beams on the strength of an imposed uniform magnetic field is obtained. The results are aimed to assess the potential of MHEs to design acceleration sensor systems with an adaptive magnetically controllable sensitivity range.

1. Introduction

At present, the development of modern technologies in materials science and chemistry leads to further possibilities for carrying out new materials with exceptional magnetic properties. One special class of such smart materials is magnetic hybrid elastomers (MHEs), which consist of both magnetically hard and soft microparticles embedded into a non-magnetic elastic matrix. It is known that their properties can be changed sufficiently by means of applied magnetic fields [1]. The reasons for that are interactions between the different types of magnetic filler and the matrix in a microscopic scale and the subsequent structure formation of the particles.

MHEs show not just pure passive and active effects that elastomers containing only one type of particles (magnetically hard or soft) would have [2–6]. The interplay of the magnetic hybrid filler results in a complex distribution of the magnetic field, which in turn influences the field reaction of the material itself. These specific features of MHEs can be identified by the magnetisation analysis based on first-order reversal curve studies [7,8]. The structural characterisation of MHEs may be also revealed by investigations using imaging techniques such as X-ray microtomography. This tool is applied to identify distribution of magnetically soft particles inside an elastomer matrix under the influence of a magnetic field [9].

Research scientists show a growing interest in the field-dependent properties and behaviour of MHEs, since they can lead to novel opportunities for basic research as well as be suitable for use in technical applications. The fact that a magnetic field might be exerted contactlessly makes such magneto-sensitive elastomers unique for a number of applications in the area of vibration isolation and damping [10,11]. A variable differential mount apparatus using an elastomer with magnetically soft particles for improving driving comfort of a vehicle is presented in [12]. In the field of biomechanics, prosthetic and orthotic devices with

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shock absorption springs made of magnetic elastomers can be adjusted to a level corresponding to an activity level of a user [13]. Various sensor devices and actuators are described in the review articles [14,15]. Among other examples are magnetic elastomers based locomotion, gripper and fluid transport systems [16–18].

The present work reports investigations on MHEs for their technical implementation as sensor systems with adaptive magnetically controllable sensitivity range. We synthesise and characterise elastomer materials with a complex hybrid filler based on large magnetically hard grains of FeNdB and small magnetically soft carbonyl iron particles. Macro beam samples of the special geometry are made from the fabricated material with a molding process. After the polymerisation, a part of the samples is magnetised in a pulsed magnetic field in order to obtain a remanence magnetisation along the beam's length. Characterisation of the magnetic properties of the MHE material are carried out using experimental methods.

One of the main objectives of this research work is to assess the potential of MHEs to design sensor systems with complex adaptive behaviour and operating sensitivity. Considering a manufactured MHE beam with one end fixed and the other one free as a prototype of a functional sensing element, its vibrational behaviour is investigated experimentally in detail. The emphasis is on the possibility to identify unambiguously the deflection of the MHE by magnetic field distortion measurements that will allow to use such element as a part of an acceleration sensor for detection of external mechanical stimuli of the environment. Moreover, investigations are aimed to show that the material properties, and therefore the sensitivity range, of the MHE sensing element can be specifically adjusted by means of an imposed magnetic field control.

2. Preparation of magnetic hybrid elastomers

2.1. Materials and synthesis

MHEs feature a composition of magnetically hard particles of FeNdB and magnetically soft particles of carbonyl iron filling a polymeric matrix. The matrix is prepared from a two-component 'SIEL' resin.[1] The two components of the resin are a low-molecular substance containing vinyl-groups (A) and a hydride-containing component (B):

(A) $((CH_3)_3SiO(((CH_3)_2SiO)_a(CH_3(H)\,SiO)_b)_xSi(CH_3)_3$
(B) $(CH_2CH)_3SiO[CH_3SiO]_ySi(CHCH_2)_3)$.

First mixed together and then with the magnetic hybrid filler, they are subjected to polymerisation at elevated temperature in the presence of a complex platinum catalyst: $((CH_2{=}CH)_3SiO[CH_3\text{-}SiO]_y\text{–}Si(CH = CH_2)_3$+Pt-catalyst),which results in the reaction

$$\cong \mathrm{Si} - \mathrm{CH} \ = \ \mathrm{CH}^2 + \mathrm{HSi} \cong [\cong \mathrm{SiCH}^2\mathrm{CH}^2\mathrm{Si} \cong]^n.$$

In order to suppress aggregation of the magnetic powders and provide them lyophobic properties as well as improve their compatibility with liquid silicone, the powders are modified by treatment with a hexane solution of a mixture of the water-repelling agent and polydimethylsiloxane. For iron powders with particle sizes in a range of 3–10 μm, the concentration of the modifying agent amounts to 1% of the mass of the powder. In the case of FeNdB, the amount of the modifier is 0.3 wt.%. The mixture of the powders with the modifying solution is then treated on a roller dispenser and finally dried.

[1] A product of State Scientific Research Institute of Chemistry and Technology of Organoelement Compounds, Moscow, Russia.

The particles of the magnetically hard FeNdB and the magnetically soft carbonyl iron are of sizes ranging in 40–100 μm and 3–10 μm, respectively. Owing to the fact that they are obtained by grinding amorphous ribbons with a thickness in the range of 20–30 μm, FeNdB particles possess irregular shapes. Such particles have problems with compact packing in the composite, which results in a decrease of their maximally possible concentration to 70 wt.% at best. In order to increase the filling of the composite and its magnetic susceptibility, a powder of carbonyl iron is added into the composition, which makes it possible to fill the space appearing between irregularly shaped particles. The concentration of carbonyl iron in our specimens reaches 25 wt.%.

Fig. 1 (a) depicts a common shape of FeNdB particles, which is obviously irregular. Imposition of a magnetic field on a underpolymerised composition leads to the formation of chain-like structures by the particles, see Fig. 1(b).

The addition of magnetically soft particles into the composition, Fig. 2(a), followed by its magnetising results in that the smaller particles form structures around magnetised magnetically hard ones, see Fig. 2(b).

Influence made by the magnetic field during polymerisation results in the formation of chain-like structures by the magnetically hard and soft particles. Magnetically soft particles are positioned along the chains formed by magnetically hard particles (Fig. 3).

2.2. Sample geometry

For the experimental investigations, four MHE samples with the configuration of straight T-shaped beams are prepared, see Fig. 4. To produce each sample, liquid composition with the combined hybrid filler content of 80–82 wt.% was poured in an aluminium mold and then subjected to polymerisation at 150 °C during an hour. After that, samples 1, 2 and 3 were pre-magnetised with a pulsed magnetic field of 2 T applied along the beam's length. The direction of the applied magnetic field is shown in Fig. 4. Sample 4 was left untreated at this stage.

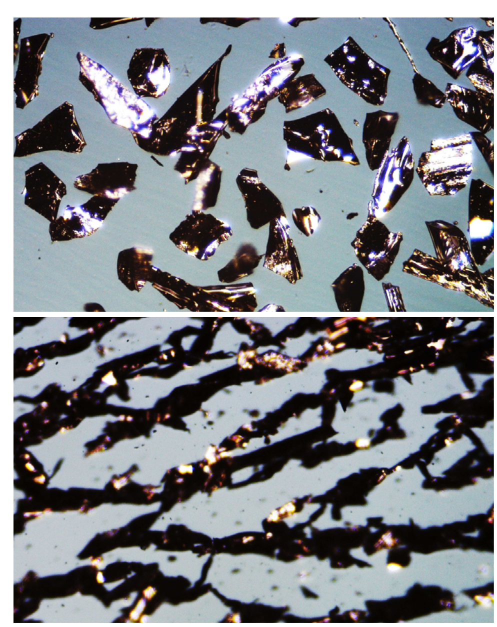
(a)
(b)


Fig. 1. (a) Magnetically hard filler of a magnetic elastomer. (b) Chain-like structures formed by the magnetically hard filler of an elastomer polymerised under a magnetic field.