Journal of Industrial and Engineering Chemistry 18 (2012) 1666–1669

Contents lists available at SciVerse ScienceDirect

Journal of Industrial and Engineering Chemistry

journal homepage: www.elsevier.com/locate/jiec

The influence of the magnetic field on the elastic properties of anisotropic magnetorheological elastomers

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ARTICLE INFO

Article history:
Received 24 November 2011
Accepted 3 March 2012
Available online 10 March 2012

Keywords:
Magnetorheological elastomer
Silicone rubber
Carbonyl iron
Thermal decomposition
Microwaves
Iron nanoparticles

ABSTRACT

This paper deals with the process of achievement of anisotropic magnetorheological elastomers (MREs), based on silicone rubber and iron nanoparticles. Plane capacitors are manufactured with MREs. The capacity C of the plane capacitors is measured as function of the intensity H of the magnetic field. By using the approximation of the dipolar magnetic moment and the ideal elastic body model, respectively, the tensions and deformations field and respectively the elasticity module of MREs function of H have been determined, for magnetic field values of up to 1000 kA/m. The obtained results are presented and discussed.

1. Introduction

Magnetorheological elastomers (MREs) and magnetorheological suspensions (MRSs) are active magnetic materials, consisting of a matrix in which magnetic particles are dispersed. As their mechanical and rheological properties are well controlled by applied magnetic fields, these materials are of interest in various applications. Unlike the MRSs, in which long term particles deposition often occurs [1–4] the stability of the MREs is ensured by inserting the particles in polymer chains [5–14]. The capabilities of MREs have received an increasing interest cluring last decades. Thus, Kaleta et al. [5] produced isotropic and anisotropic MREs based on thermoplastic rubber and iron microparticles, and carried out a study of their static magnetomechanical properties. Fan et al. [6] manufactured MREs based on silicone rubber and carbonyl iron microparticles (in different mass fractions) and studied their both static and dynamic magnetomechanical properties. These MREs' properties are used in various systems. Thus, Deng et al. [7] proposed magnetomechanical damping devices based on adaptive tuned vibrations (note that the damping mechanism in MREs differs from that in magnetostrictive materials [8,9]).

The present author [10–14] made magnetic field-controlled magnetoresistive dipoles and electric quadropoles, based on silicone rubber and iron microparticles. The devices are of interest in developing stress or strain sensors and transducers for chemically agressive environments. Following this research direction, the present paper deals with fabrication of silicone rubber-based MREs, containing iron nanoparticles formed by thermal decomposition (microwave-assisted) of carbonyl iron dispersed in a viscous mixture of polydimethylsiloxane and silica. The magnetomechanical properties of the as-obtained MREs are studied by means of the plane capacitor method.

2. Experiment

The obtaining of MRE as an anisotropic dielectric material in a plane capacitor comprises two steps. During the first step, carbonyl iron powder is mixed with liquid silicone rubber, followed by in situ thermal decomposition; as a consequence anemometric iron particles result. In the second stage the mixture is injected together with catalyst between two parallel copper plates, followed by polymerization in magnetic field.

2.1. In situ obtaining iron nanoparticles

The used precursors are:

- silicone rubber (SR) of type *RTV-3325* (Bluestar Silicones) consisting of a viscous mixture of polydimethylsiloxane and silica; the ignition temperature of the mixture is above 673 K [15],
- carbonyl iron (CI), produced by Sigma, as a powder of grain size ranging between 4.5 μm and 5.4 μm and iron content exceeding 97%. It thermally decomposes starting from 503 K [16,17]. Four samples S_i ($i = 1, 2, 3, 4$) with different compositions were

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1226-086X/$ – see front matter
doi:10.1016/j.jiec.2012.03.006

Table 1
Samples and microwave heating parameters.

Sample	Materials	$10^6 \times V$ (m^3)	P (W)	t (s)	T_S (K)
S_1	SR	27.0	440	720	423
	CI	1.5			
S_2	SR	25.5	264	600	438
	CI	3.0			
S_3	SR	22.5	264	600	440
	CI	6.0			
S_4	SR	19.5	136	480	450
	CI	9.0			

Note: SR, silicone rubber; CI, carbonyl iron; P, nominal power of the microwaves; t, time; T_S, sample surface temperature.

prepared, and there were heated in a microwave oven (model MM820CPB-*Midea*). The compositions and heating parameters are given in Table 1. Using a *AX-6520* (AxioMat) pyrometer, the temperature T_S of the sample monitored.

The magnetic behavoiur of the samples was examined in 50 Hz ac fields, by means of an integrating fluxmeter [18]; in Fig. 1 the hysteresis loop of the sample S_4 is shown (similar loops resulted for the lower particles density samples S_1, S_2 and S_3). Since the loop is very close to the anhysteretic, from fitting with a Langevin-type [19] function (the coefficient of determination was $r^2 = 0.99992$), a value $d_m = 3.5$ nm resulted for the mean diameter of the iron particles.

The carbonyl iron powder is electroconductive. In microwave field, each microparticle, situated in the liquid matrix, is inductively heated and, at temperatures beyond 503 K, it decomposes thermally [16]; iron atoms and carbon monoxide molecules result. As an effect of pressure as-developed in the liquid matrix, the carbon monoxide is ejected to the surface and then evacuated by the exhauster of the microwave oven. The dispersed Fe atoms move toward colder regions; if in these regions the temperature is close to the dew point, crystal nuclei occur, grow by further condensation and nanoparticles form. Then, complex bonds occur between the surface Fe atoms and the polydimethylsiloxane free radicals, leading to hydrodynamic stabilization of the as-formed nanoparticles [17].

2.2. MRE-based capacitors

Each of the samples Si is mixed and homogenized with 1.5×10^{-6} m^3 catalyst of type 6H (Bluestar-Silicones). The obtained mixture is injected between two copper plates which are pressed until the distance between them becomes 0.0002 m. The material, in liquid state, is polymerized in a transverse magnetic field of 500 kA/m ± 10%. The polymerization of the silicone rubber takes place at room temperature (297 K ± 10%). The reaction is completed within 24 h. Finally, plane capacitors with dielectric material based on silicone rubber and iron nanoparticles are obtained, having volume fractions of $\varphi_1 = 0.05$; $\varphi_2 = 0.10$; $\varphi_3 = 0.20$ and $\varphi_4 = 0.30$.

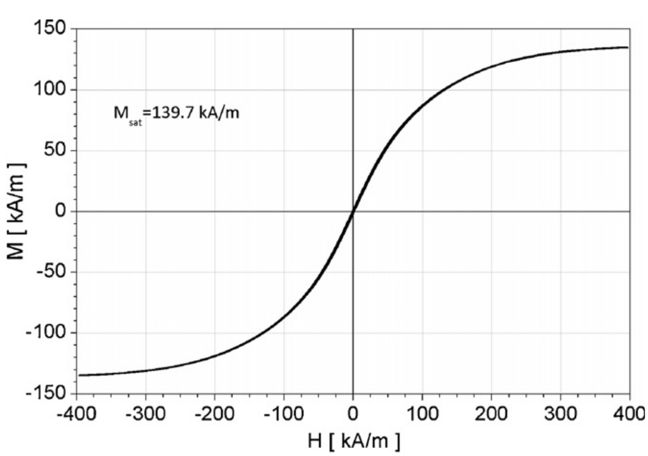

Fig. 1. The magnetization curve of the S_4.

3. Theory

For simplicity, assume that the Fe nanoparticles from the elastic matrix have the same size; let d_m be their diameter.

Due to the polymerization in a magnetic field, the nanoparticles form linear chain, uniformly distributed within the elastic matrix. The distance between the chains is assumed sufficiently large. This means that when a magnetic field is applied, the interaction between the chains is negligible compared to that between the nanoparticles.

The distance between the nanoparticles in the chain is assumed equal with the average initial distance [3]:

$$d_0 \approx d_m \varphi_i^{-1/3} \quad (1)$$

where φ_i is the volume function.

Under the magnetic field, the nanoparticles from the chain are magnetized, parallel to the field each having the magnetic moment [3]:

$$m = 0.5\pi d_m^3 H \quad (2)$$

Let the relative magnetic permeability of the elastic matrix $\mu_e \approx 1$ and that of the iron nanoparticles $\mu_p \gg \mu_e$. between two neighboring nanoparticles, an attractive force [3,10–12]:

$$F_{m_1} = -\frac{3\mu_0 \mu_e m^2}{\pi d^4} \quad (3)$$

occurs.

where μ_0 is the vacuum permeability, and $d < d_0$ is the distance between the magnetic dipoles centers at $H \neq 0$.

The number of Fe nanoparticles from the elastic matrix corresponding to φ_i is:

$$n_i = \frac{\varphi_i V}{V_p} = 6\varphi_i \frac{Ll}{d_m^3} h_0 \quad (4)$$

where V is the volume of the dielectric (MRE), V_p is the volume of the nanoparticle, L, l and h_0 are the length, width and thickness of the MRE at $H = 0$, respectively.

The average magnetic force which is exerted upon the MRE is:

$$F_m = \frac{1}{2} n_i F_{mi} \quad (5)$$

Introducing (3) and (4) into (5) and taking into account the expression (2) for $d \approx d_m$, we obtain:

$$F_m = -2.25\pi\mu_0 Ll \frac{h_{0i}}{d_m} \varphi_i H^2; \quad (6)$$

The action of F_m will be counter-balanced by the elastic force:

$$F_{el} = k_{ei}(h_0 - h_{0i}); \quad (7)$$

where k_{ei} is the elastic constant, while h_0 and h_{0i} are the thicknesses of the dielectric for $H \neq 0$ and $H = 0$, respectively.

The equilibrium condition $\vec{F}_m = -\vec{F}_{el}$ leads to:

$$h_i = h_{0i}\left(1 - 2.25\pi\mu_0 \frac{Ll}{k_e} \frac{\varphi_i}{d_m} H^2\right); \quad (8)$$

According to of Eqs. (6) and (7) the capacity of the plane capacitor is:

$$C_{0i} = \varepsilon_0 \varepsilon_{ni} \frac{S}{h_{0i}}; \quad \text{for } H = 0; \quad (9)$$