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Composite magnetorheological elastomers as dielectrics for plane capacitors: Effects of magnetic field intensity

Maria Balasoiu [a,b,*], Ioan Bica [c]

[a] Joint Institute for Nuclear Research, Dubna, Russian Federation
[b] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[c] West University of Timisoara, Romania

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ABSTRACT

The fabrication of composite magnetorheological elastomers (MRECs) based on silicone rubber, carbonyl iron microparticles (10% vol.) and polyurethane elastomer doped with 0%, 10% and 20% volume concentration TiO_2 microparticles is presented. The obtained MRECs have the shape of thin foils and are used as dielectric materials for manufacturing plane capacitors. Using the plane capacitor method and expression of capacitance as a function of magnetic field intensity, combined with linear elasticity theory, the static magnetoelastic model of the composite is obtained and analyzed.

Introduction

Recently it has been shown that by introducing nano/microparticles in an elastic matrix one obtains materials whose properties can be modified in the presence of an external magnetic field [1–10]. In particular, it has been shown using the plane capacitor method [1], that the deformations and stresses induced in magnetorheological elastomers (MRE) based on silicone rubber (SR) and carbonyl iron (CI) microparticles are significantly influenced by the magnetic field.

Using MRE based on silicone rubber and CI, giant magnetoresistors are fabricated, whose electrical resistance is controlled by a magnetic field [2]. Also quadrupolar magnetoresistors that can be assimilated to a Hall probe are made [2,3]. By keeping a constant voltage at one gate of the circuit [2] or constant input current [3], a voltage which varies with the intensity of the applied magnetic field, is obtained at the other gate of the device.

As a consequence of the polymerization of silicone rubber with CI, in the presence of the magnetic field, deformation sensors have been obtained whose sensitivity can be tuned by different values of magnetic field intensity [4,5]. It was shown that by fabrication of composites using MRE based on polyurethane and graphene nanoparticles [6], the electrical conductivity of material can be changed reversibly in a magnetic, mechanical strain and respectively, in a thermal field. The composite materials based on polyurethane elastomers (PE), have smaller costs as compared with those based on solid materials and can be successfully used as temperature and/or magnetic field sensors, in unfriendly media.

Fabrication of composite materials based on polyurethane matrix is of relatively recent date.

By addition of additives such as nano- and microparticles [2–10], the physical properties of the polymerized elastomer can be significantly changed.

Therefore, in this paper, we fabricate plane capacitors based on polyurethane [11] elastomers doped with carbonyl iron and TiO_2 microparticles.

Using the plane capacitor method, electrical and elastic properties of the fabricated composites are studied.

Experiment

Production of MREC

Materials

The materials used for fabricating the MREC are:

- Polyurethane elastomer (PE), also known as Elastotamp (TNT-40 type), which has 2 components A and B (base and catalyst) [12];

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* Corresponding author at: Joint Institute for Nuclear Research, Dubna, Russian Federation, Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

E-mail addresses: masha.balasoiu@gmail.com (M. Balasoiu), ioanbica50@gmail.com, ioanbica50@yahoo.com (I. Bica).

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- Titanium dioxide (98.5% purity) and carbonyl iron (CI) particles from Sigma–Aldrich Company with average diameter d_m = 5 µm [13];
- Silicone rubber (SR) (RTV 3325 type) and catalyst C (6H type) from Bluestar-Silicone [14];
- Copper (Cu) band from 3 M Company [15].

Methods

First, we prepare a mixture consisting from SR (8.5 cm^3), CI (1 cm^3) and C (0.5 cm^3). The proportions of the components are chosen experimentally by successive tests. The homogenization is performed using Silent Crusher-M homogenizer from Heidolph, at 5000 rpm for about 900 s. Thus, the MRE mixture is obtained.

In the second step a volume of 25 cm^3 of component A of PE is mixed, with the same volume of component B of PE (see Section " Materials"). This mixture is heated up to 340 K for about 300 s and is further homogenized at 5000 rpm. While cooling, the mixture is obtained, and the authors named it as $(PE)_1$. Next, a volume of 22.5 cm^3 of component A of (PE) is mixed, with the same volume of component B and a quantity of 5 cm^3 of TiO_2 is added. In the same conditions and using the same device as for $(PE)_1$, the mixture $(PE)_2$ is obtained. Finally, using a volume of 22 cm^3 of component A of (PE), the same volume of component B, and 10 cm^3 TiO_2 powder, the mixture $(PE)_3$ is obtained.

Capacitors

For constructing the capacitors, we start by fabricating six Cu disks, with a diameter of 0.08 m. Each disk is glued on an isolating support (Plexiglas) with dimensions $0.10 \times 0.10 \times 0.15\ m^3$. On three out of the six disks, we glue two rings: one ring with a diameter of 0.10 m, and the second one, concentric with the first ring and drilled, and having the diameter of 0.08 m.

In the volume delimited by the smaller one and by the two plates, the mixture $(PE)_1$, and between the two rings, the MRE mixture are poured. The isolating support, is pressed over the rings with MRE and $(PE)_1$ mixtures, with the side containing the Cu disk. After polymerization, the capacitor K_1 is obtained. We proceed similarly with MRE and $(PE)_2$, and MRE and $(PE)_3$ mixtures and the capacitors K_2 and K_3 are obtained. Between MRE and $(PE)_i$ mixtures (i = 1, 2, 3) a transfer of substance is produced, since the inner ring is drilled. The volume fractions of TiO_2, Φ in MREC are: 0% for K_1; 10% for K_2; 20% for K_3.

The capacitors K_1, K_2 and K_3 have disk-shape armatures with diameter $D = 0.10$ m and the distance between them $d_0 = 0.0018$ m.

Experimental setup

The experimental setup used to study the effect of magnetic field on MREC is shown in Fig. 1. The setup consists of two functional blocks A and B.

Block A contains a Weiss electromagnet (Phylotex type) connected to a continuous current source. Block B contains a Gaussmeter GM-04 connected to a Hall probe (T4002 type) and a capacimeter CM-7115A.

The capacitor K_i (i = 1, 2, 3) is fixed between the poles N and S of the electromagnet.

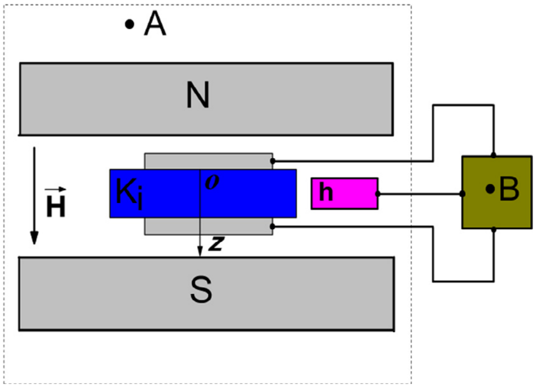

Fig. 1. Experimental setup (overall configuration): (A) the block for magnetic field generation; (B) the block for measurement of the magnetic field intensity and electrical properties (voltage, capacitance, resistance, electric field intensity); H, the magnetic field intensity vector; h, the Hall probe; N and S, the poles of the electromagnet; k_i (i = 1, 2, 3) the capacitors; Oz, the coordinate axis.

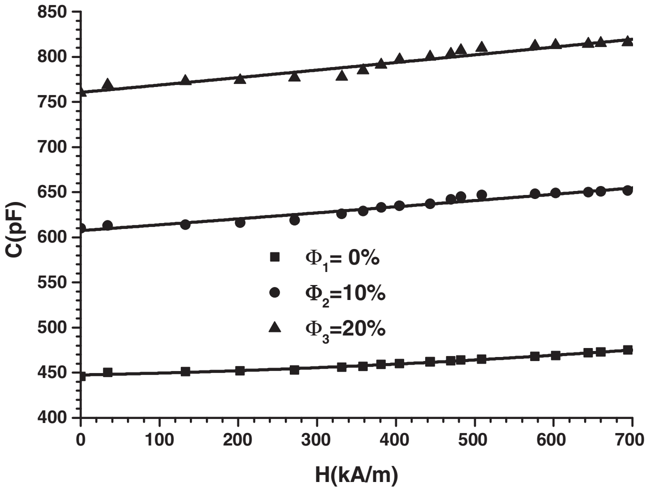

Fig. 2. Capacitance C as a function of H, for various values of volume fraction Φ_i (i = 1, 2, 3) of TiO_2. Dots – experimental values, continuous line – polynomial fit.

Experimental results and discussions

For each value of intensity H one measures the capacitance C at the terminals, and the measured values $C = C_\Phi(H)$ for each TiO_2 particle volume fraction Φ, are shown in Fig. 2. Neglecting edge effects, the capacitance can be calculated according to:

$$C = \varepsilon_0 \varepsilon_r \frac{S}{d}, \quad \text{for } H \neq 0 \tag{1}$$

and

$$C_0 = \varepsilon_0 \varepsilon_r \frac{S}{d_0}, \quad \text{for } H = 0 \tag{1'}$$

where ε_0 is the absolute permittivity of vacuum, ε_r is the relative permittivity of MREC, S is the common area between the plates, d is the distance between plates (for $H \neq 0$), and d_0 is the distance between plates (for $H = 0$).

Using numerical values $\varepsilon_0 = 8.85$ pF/m, D = 0.10 m and d_0 = 0.0018 m in Eq. (1) using $C_0[pF]$ one obtains:

$$\varepsilon_r = 0.0254 C_0 \quad \text{for } H = 0 \tag{2}$$

The capacitance is measured without applying a magnetic field. The obtained values are introduced in Eq. (2) and the values of ε_r are obtained (Table 1). The data show that ε_r increases with increasing Φ and is not dependent on H.

At the interface between MRE and $(PE)_i$ through the holes drilled into the first ring, CI particles diffuse into PE, and TiO_2 particles into MRE.

The magnetic dipoles are arranged on the direction of magnetic field lines. The dipolar magnetic moment inside the elastic matrix can be calculated from [2]:

$$m \cong 0.5\pi d_m^3 H, \tag{3}$$

where d_m is the average diameter of the CI microparticles and H is the intensity of magnetic field.

Between two neighboring dipoles, separated by a distance z, dipolar interactions occur. In a uniform magnetic field, for $z \sim d_m$, the intensity of dipolar interaction can be calculated with formula [16]:

$$F_d = \frac{-3\mu_0 m^2}{8\pi z^4}, \tag{4}$$

where μ_0 is the magnetic permeability of vacuum.

The number of dipoles N_m inside the matrix can be calculated using the formula [16]:

$$N_m = \frac{V_m}{V_p} = \frac{3 d_0 D^2 \Phi_m}{2 d_m^3}, \tag{5}$$

where $V_m = \frac{\pi}{4} D^2 d_0 \Phi_m$, is the volume occupied by magnetizable particles, and $V_p = \frac{\pi}{6} d_m^3$ is the volume of an average CI particle, and Φ_m is the volume fraction of CI microparticles.

The number of dipoles along MREC thickness can be obtained from:

$$N_z = \frac{d_0}{d_m}. \tag{6}$$

For $N_z \gg 1$, the magnetic force due to a single dipole column is defined as

$$F_z = N_z F_d,$$

and using Eqs. (4) and (6) it takes the form:

$$F_z = -\frac{3\pi\mu_0}{32} d_0 d_m H^2 \tag{7}$$

The number of dipole chains in MREC is

$$N = \frac{N_m}{N_z},$$

and using Eqs. (5) and (6), we obtain:

$$N = \frac{3}{2}\Phi_m \left(\frac{D}{d_m}\right)^2 \tag{8}$$

The magnetic force induced by H in MREC is $F_m = N F_z$, and together with Eqs. (7) and (8) it becomes:

$$F_m = \frac{-9\pi\mu_0 \Phi_m D^2 d_0 H^2}{64 d_m} \tag{9}$$

Under the action of force F_m, in the matrix is induced an elastic force of the form [2–6]

$$F_{el} = k(d - d_0) \tag{10}$$

At equilibrium results: $F_m = F_{el}$.

From Eqs. (9) and (10), at equilibrium we obtain:

$$d = d_0 \left(1 - \frac{9\pi\mu_0 \Phi_m D^2 H^2}{64 k d_m}\right) \tag{11}$$

By introducing Eq. (11) in Eq. (1) we obtain the dependence of capacitance with H, namely:

$$C = \frac{C_0}{1 - \frac{9\pi\mu_0 \Phi_m D^2 H^2}{64 k d_m}} \tag{12}$$

where C_0 is the capacitance of plane capacitors, at $H = 0$.

For, $\Phi_m = 10\%$, $D = 0.10$ m, and using Eq. (12) where H [kA/m], C [pF] and k [N/m] we obtain:

$$C = \frac{C_0}{1 - \frac{110.9 H^2}{k}} \tag{13}$$

From Eq. (13) the elasticity constant is obtained:

$$k = \frac{110.9 H^2}{1 - \frac{C}{C_0}} \tag{14}$$

or

$$k = -\varepsilon H^2 \tag{14'}$$

where from Eqs. (1) and (1′) results

$$\frac{d}{d_0} = \frac{C_0}{C}$$

and

$$\varepsilon = -\left[1 - \frac{C_0}{C}\right] = -\left[1 - \frac{d}{d_0}\right] \tag{15}$$

represents the linear specific deformation.

In Fig. 2 the capacitance C measured as a function of H, for various values of volume fraction Φ_i of TiO_2 is presented.

By application of magnetic field, inside MREC the tension is induced:

$$\tau = -\frac{4F_{el}}{\pi D^2} = -\frac{4 k d_0 \left(\frac{d}{d_0} - 1\right)}{\pi D^2} \tag{16}$$

Using Eq. (15), Eq. (14) becomes:

$$\tau = -\frac{4F_{el}}{\pi D^2} = -\frac{4 k d_0}{\pi D^2}\left[\frac{C_0}{C} - 1\right] = -E\varepsilon \tag{17}$$

where

$$E = \frac{4 k d_0}{\pi D^2}, \tag{18}$$

is the elastic modulus.

Introducing in Eq. (15) the experimental values of C_0 (Table 1) and $C = C(H)$ (Fig. 2) for Φ_i i = 1, 2, 3, the corresponding dependences of specific deformation $\varepsilon = \varepsilon_\Phi(H)$ are obtained (Fig. 3). It

Table 1
Values of C_0 and ε_r for TiO_2 particle volume concentration, Φ.

No.	Φ [%]	C_0 [pF]	ε_r
1	0	446	11.35
2	10	610	15.52
3	20	760	19.38

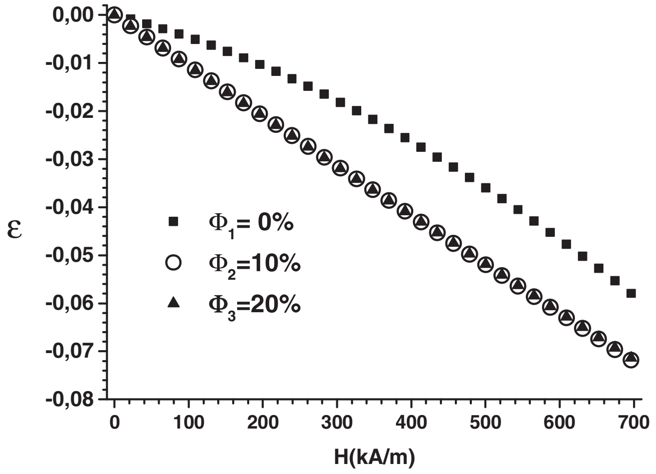

Fig. 3. Linear specific deformation $\varepsilon = \varepsilon_\Phi(H)$ for various values of volume fraction Φ_i (i = 1, 2, 3) of TiO_2.

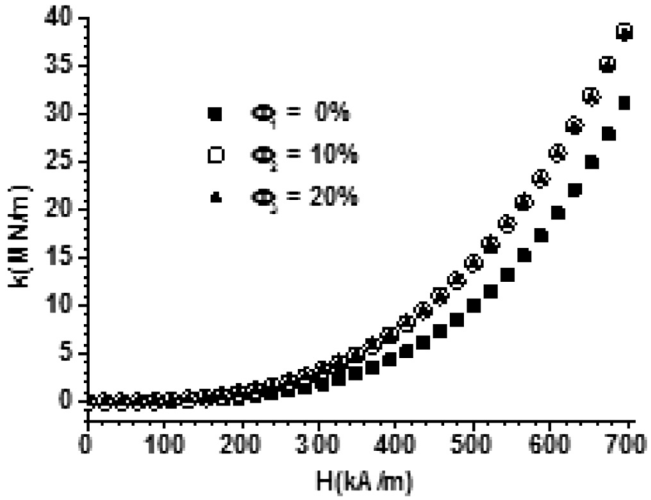

Fig. 4. Elastic constant $k = k_{\Phi}(H)$ for various values of volume fraction Φ_i (i = 1, 2, 3) of TiO_2.

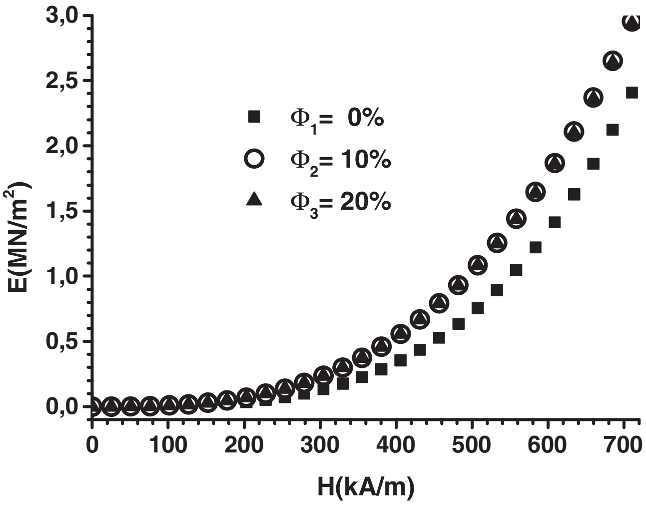

Fig. 5. Elastic modulus $E = E_{\Phi}(H)$ for various values of volume fraction Φ_i (i = 1, 2, 3) of TiO_2.

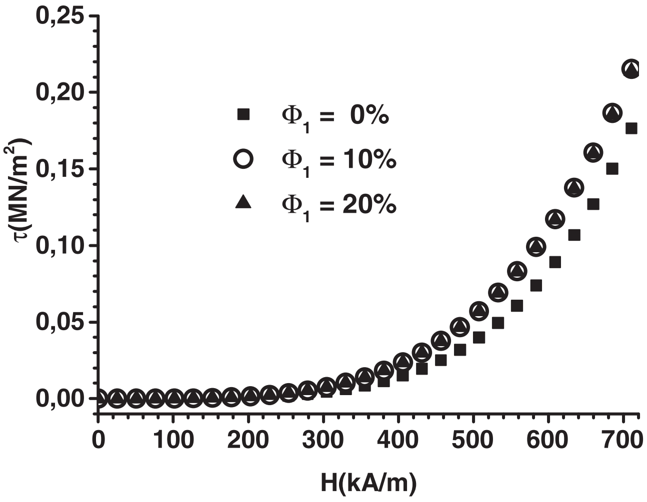

Fig. 6. Tension τ induced inside MREC by H for various values of TiO_2 microparticles volume fraction Φ_i (i = 1, 2, 3).

can be seen from Fig. 3 that the relative contraction of the samples increases with increasing magnetic field. For Φ_i: 10% and 20% the relative contraction of MREc depends linearly on H.

With the values of $\varepsilon = \varepsilon_{\Phi}(H)$ from Fig. 3 inserted into the expression (14′), we get the dependence $k = k_{\Phi}(H)$ presented in Fig. 4. The elastic constant (Fig. 4) increases with increasing H and it is influenced by the TiO_2 microparticles' presence.

For $k = k_{\Phi}(H)$ determined from Fig. 4 and introduced in Eq. (18), where d_0 and D are known, $E = E_{\Phi}(H)$, as shown in Fig. 5, is obtained.

As expected, the allure of functions $E = E_{\Phi}(H)$ in Fig. 5, is identical to those of $k = k_{\Phi}(H)$ in Fig. 4.

Further, using $E = E_{\Phi}(H)$ from Fig. 3 and $E = E_{\Phi}(H)$ from Fig. 5 in Eq. (17), the variation of τ function of H for Φ_i: 0%, 10%, 20%, is obtained (see Fig. 6).

It can be seen (Fig. 6) that the tension τ induced in MREC increases with H and is influenced by the presence of TiO_2 microparticles.

Conclusions

A new material composed of a magnetorheological elastomer, composed from silicone rubber doped with carbonyl iron particles, coupled with an electroreologic one, based on polyurethane elastomers doped with TiO_2 microparticles, is presented in the paper.

The fabrication from the new composite of plane capacitors based on polyurethane elastomers doped with carbonyl iron and TiO_2 microparticles, is shown.

It is demonstrated that its elasticity is significantly influenced by the magnetic field strength and respectively, the volume fraction of TiO_2.

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