Journal of Magnetism and Magnetic Materials 322 (2010) 3337–3341

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Shape effect in the magnetostriction of ferromagnetic composite

G. Diguet [a,b,*], E. Beaugnon [a], J.Y. Cavaillé [b]

[a] CNRS–CRETA, 25 avenue des martyrs, 38042 Grenoble, France
[b] MATEIS, UMR5510, CNRS, INSA-Lyon, 7 avenue Jean Capelle, 69621 Villeurbanne, France

ARTICLE INFO

Article history:
Received 17 November 2009
Received in revised form
21 March 2010
Available online 12 June 2010

Keywords:
Shape effect
Ferromagnetic particle
Elastomer
Demagnetizing field
Filling factor
Composite Young's modulus

ABSTRACT

The magnetostriction of composite consisting of a soft matrix, non-magnetic, randomly filled by ferromagnetic particles is measured. The measured elongation on cylinder-shaped samples displays shape dependence. A model based on the demagnetizing field and the effective Young's modulus is provided. Both calculation and measurement show a positive magnetostriction with larger values as the samples are flatter. The model is derived to have the behavior of the elongation as a function of the filling factor. An expression of the optimal filling factor, providing a maximal strain, is also expressed.

1. Introduction

Magnetic rheological elastomers (MRE) are composite materials made of ferromagnetic particles embedded within a soft and non-magnetic matrix. When exposed to a magnetic field, these materials change their elastic properties. Magnetic interactions between particles and mechanical interactions between matrix and particles are keys to the overall properties of the MRE.

These magnetic interactions between particles are very sensitive to their distribution inside the matrix. MRE are composite with particles randomly distributed inside the matrix whereas field structured elastomers (FSE) are defined as MRE having a specific distribution of the particles; they can be gathered into some sheet-like particles or chain-like particles distribution [1]. Exposed to a specific external magnetic field, while the matrix is curing, the particles organized themselves into such structures. These distributions change the magnetic behavior of the composite [1]. Having an anisotropic distribution of the particles, its mechanical properties are also different from having an isotropic distribution. Apparent Young's modulus of the composite is larger for FSE than MRE [2]. They act like a fiber-filled composite.

In general, the whole magneto elasticity behavior is tuned by its inner distribution and external solicitation. Composite will change their magnetization under an external stress [3]. Both anisotropic and isotropic composite will change their mechanical properties but in different ways when they are exposed to a magnetic field [4]. This is known as the delta-E effect. Magnetostriction of the composite also appears. When MRE samples are placed in an external magnetic field, they change their shapes. This phenomenon is highly sensitive to the distribution of the particles inside the composite. It has been found that FSE will contract in an applied magnetic field parallel to the columns of particles unlike to MRE that will dilate [5].

In the present work, we are interested in the global deformation of a random-filled composite exposed to a uniform and static magnetic field. Length change measurement of such composite shows a large positive magnetostriction. We have succeeded in measuring a 9.2% strain.

A theoretical model, based on demagnetizing and elastic energy, explains the positive strain of magnetized composites in the magnetic field. This idea was already known for a spherical drop of magnetized fluid in a homogeneous field [6]; that spherical drop turns into an elongated ellipsoid to decrease the demagnetizing energy. A conducting sphere in an electric field also behaved in the same ways [7]. Raikher and Stobolv [8] has written a theoretical article on the elongation of a spherical ferrogel with a low Young's modulus, therefore foreseeing possible large strain with such materials. Here, we focused on the impact of that demagnetizing energy on the strain. We provide below an extension to the model that takes into account the initial composite shape and the effective parameter of the MRE, such as the magnetization and Young's modulus. In this way, we prepared samples with different shape to change their demagnetizing energy, then the amplitude of deformation. We were also interested in the filling factor effect on the strain.

* Corresponding author at: CNRS–CRETA, 25 avenue des martyrs, 38042 Grenoble, France. Tel.: +33 4 76 88 90 34; fax: +33 4 76 88 12 80.
E-mail address: gildas.diguet@grenoble.cnrs.fr (G. Diguet).

0304-8853/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmmm.2010.06.020

2. Experimental

2.1. Magnetic particles

The magnetic particles, provided by SPETELEC, are made of 98.7% iron. These particles are spherical with a diameter close to 5 μm. To determine the iron magnetization hysteresis, we used a vibrating sample magnetometer. Measurements were made in the external magnetic field increasing from -1 to 1 T and decreasing back to -1 T. A low magnetic remanence and a high saturation magnetization $\mu_0 M_{sat}$=2.08 T were found [9].

2.2. Composite

Sample dilatation has been measured using an electromagnet to generate a uniform magnetic field on the sample. This electromagnet is made up of a couple of coils which have been placed into a Helmholtz device. A magnetic core was added to canalize the magnetic flux that provides a uniform magnetic field on the samples. Electrical current ranged from 0 to 160 A that creates a magnetic field up to 1.2 T. The sample was placed inside this device and was observed by using a 768×576 CCD camera from ELMO. Pictures were taken at every 0.14 T, at both increasing and decreasing field. Displacement between each step is determined by image analysis.

The dynamic Young's moduli of composite were measured with a Viscoanalysor VA 2000 (Metravib R.D.S.) with low frequencies solicitation. At 5 Hz, an $E_0 = 1.4 \times 10^5$ Pa modulus was measured at room temperature for an unfilled composite.

Isotropic composites were prepared by hand-mixing iron particles with a silicone elastomer from DALBE, which has been chosen for its low glass transition temperature after curing, which leads to an elastomeric behavior at room temperature. A catalyst was added to the mixture to harden it. A procedure of degassing was then applied to remove bubbles; the mixture was placed in a vacuum chamber at 1 mbar for 5 min. The mixture was kept in a cylindrical mold at room temperature for 24 h.

To test the shape effect, cylindrical shaped samples were prepared, with different aspect ratio, defined as length c divided by diameter a. Experimental aspect ratio ranged from 0.33 to 1.46. These samples were filled 30% (vol) by iron particles.

Another set of samples was prepared in order to have the filling factor behavior of the magnetostriction. These samples have an aspect ratio set as 0.62. The experimental filling factor ranged from 5% to 35% (vol).

3. Calculation

The energy E of interaction of a magnetic particle, with a magnetic moment m, in a magnetic induction B is

$$E = -\vec{m} \cdot \vec{B} \tag{1}$$

Now we will expand the calculation on the whole set of saturated magnetic particles and consider this set as an equivalent magnetic body with effective parameters. The interaction energy of a set of n magnetic particles is the dipolar energy E_D

$$E_D = -\frac{1}{2}\sum_{i=1}^{n}\sum_{j=1, j\neq i}^{n} \vec{m}_i \cdot \vec{B}_{ij} \tag{2}$$

where B_{ij} is the magnetic induction on the moment m_i created by all the other moments m_j is calculated as the dipolar field. This dipolar energy is the work for gathering isolated magnetic moments into the volume. The $\frac{1}{2}$ factor is added to avoid the double summation of reciprocal terms. Calculation of the inter-particles force inside the cylinder based on that dipolar energy explains the positive elongation of a randomly filled composite [9]. In this energy a shape-dependent term can be extracted, the demagnetizing energy.

In the case of the MRE composite, which is a set of magnetic moment randomly placed in the elastic volume, we can write that demagnetizing energy E_d as

$$E_d = \tfrac{1}{2}\mu_0 n_{sample} M_{composite}^2 V_{composite} \tag{3}$$

$M_{composite}$, $V_{composite}$ and n_{sample} are, respectively, the magnetization of the composite, its volume and its demagnetizing shape coefficient (or factor). $\mu_0 = 4\pi \times 10^{-7}$ is the permeability of the vacuum.

Because of the demagnetizing shape coefficient, which is (for cylinders and ellipsoids) a function of ratio length on diameter [10], this demagnetizing energy is highly sensitive to the shape of the composite. A flat sample will hold a larger energy than a long one. Hence, to reduce its demagnetizing energy, a magnetized material will elongate as described in Fig. 1. The developed idea below is the shape dependence on the strain: flatter samples, holding a larger demagnetizing energy, will elongate with larger amplitude than long sample.

Considering a change of shape with a volume unchanged (which is the case for elastomer), the elastic energy E_{elas} can be written as [7]

$$E_{elas} = \tfrac{1}{2}E_{composite}\varepsilon^2 V_{composite} \tag{4}$$

where $E_{composite}$ is the effective Young's modulus of the composite and ε is the strain. That strain results in reduction of the demagnetizing energy of the composite

$$\Delta E_d = \tfrac{1}{2}\mu_0 M_{composite}^2 \Delta n_{sample} V_{composite} \tag{5}$$

The total change energy involved in the transformation is then written as the sum of the change of demagnetizing and elastic energy

$$E_{tot}(\varepsilon) = \tfrac{1}{2}\,\mu_0 M_{composite}^2 \Delta n_{sample} V_{composite} + \tfrac{1}{2}E_{composite}\varepsilon^2 V_{composite} \tag{6}$$

The total energy plotted as a function of the elongation is presented in Fig. 2 for different aspect ratio of samples. This curve shows the conversion of the demagnetizing energy into elastic energy. For low strain, the total energy decreases; which means the reduction of the demagnetizing energy is the dominant component here. As the sample elongates its aspect ratio increases; the demagnetizing energy decreases. Then the total energy reaches a minimum and increases for larger strain. From this minimum, the elastic energy is the dominant component of the total energy. The effective elongation ε of a specific sample is reached when the total energy is minimized. The curve, of the whole energy as a function of elongation, has been plotted with different aspect ratio; the minimum is reached for different values

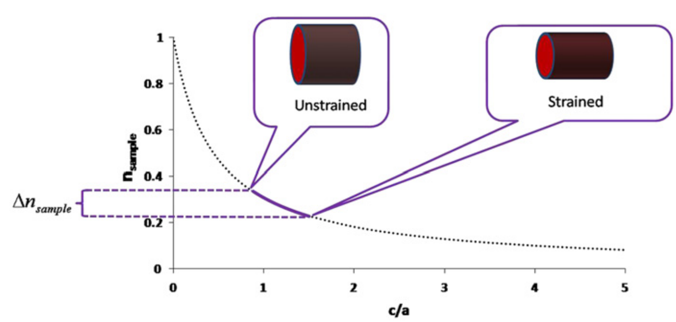

Fig. 1. Change of demagnetizing factor of cylinder during the elongation.