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ORIGINAL PAPER

Magnetoresistive Effect in Magnetoactive Elastomers

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Abstract A study of the influence of magnetic field on the resistivity of the magnetoactive (magnetorheological) elastomer has been conducted. The material consisted of a soft polymer matrix and magnetic fillers being powders of Fe, Ni, and the Fe–Nd–B alloy. Under the influence of the field with a value of 300 mT, the elastomer exhibited the magnetoresistive effect: The specific electric resistivity of the material was noticed to decrease by 3 orders. In addition, a significant dependency of the ability to conduct electric current was found on mechanical influence (piezoresistive effect) and combined influence of mechanical force and magnetic field. In the case considered, the behavior of the electroconductivity has a complex character.

Keywords Magnetoactive elastomer · Magnetorheological elastomer · Magnetoresistive · Piezoresistive effect · Pressure sensor

1 Introduction

At present, an intense scientific interest is drawn to the studying of magnetoactive (MAE), or otherwise, magnetorheological elastomers (MRE), magnetic materials of a novel type, which belongs to the class of so-called "smart materials" exhibiting the capability of changing their properties under the influence of magnetic field [1–5]. The most widely investigated feature of this material is the magnetorheological effect, namely the changes in its viscous and elastic properties caused by the field, which is the origin of the term "magnetorheological elastomer." A detailed study of this material also unveiled its other specifics, such as the ability to exhibit the magnetodeformational and magnetostrictive effects. The former has been studied by Zrínyi in magnetic gels and Nikitin in magnetoplastics [1–3]. This phenomenon is based on the deformation of the material in nonhomogeneous magnetic fields, which was found out to reach 30 and 200 % for magnetic gels and magnetoelastics, respectively [1–4].

The material exhibits the shape memory effect based on the ability to gain pseudoplasticity in the external magnetic field, which means that until the field if off, the sample will retain the shape it acquired after being subjected to a mechanical influence. The initial shape is regained after the sample has been taken out of the field [3–6].

The material possesses all its external features owing to its internal property, namely the ability to restructure under the influence of magnetic field. The particles of the magnetic filler chaotically distributed in the polymer matrix form chain-like textures due to dipole-dipole interaction. When the field has been off, the elastic forces of the polymer matrix return the particles to the initial positions. At the same time, the displacements of the particles come up to 1–2 diameters of an average particle. Qualitatively, this effect may be observed on the surface of the magnetoelastic placed into a strong homogeneous magnetic field. A columnar structure, which may be seen, is the grounds for a conclusion about the particles lining up into an arrangement inside the material. In later experiments, this effect was observed under a metallographic microscope making it possible to observe how magnetic particles inside the polymer matrix change their places under the influence of magnetic field [4].

The presence of the structuring effect on condition that the particles of the magnetic filler are electroconductive, as

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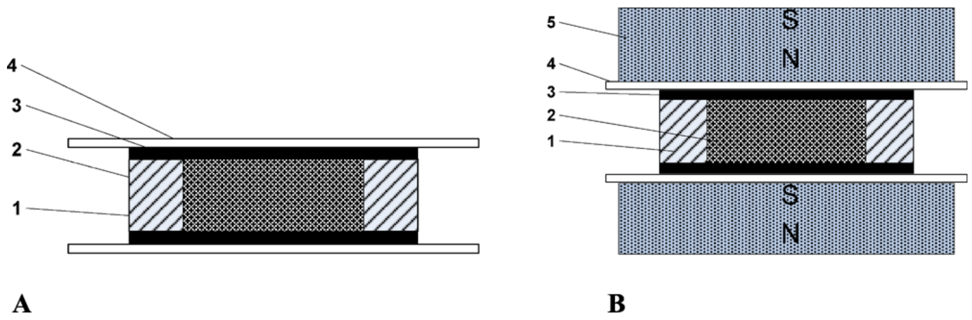

Fig. 1 Scheme of preparation of a MAE sample. 1—cast; 2—MAE sample; 3—electrodes; 4—glass plate; 5—constant magnets

is iron powder, for instance, must lead to changes in the ability of the material to conduct electric current under the influence of magnetic field. This phenomenon is known as the magnetoresistive effect.

A study of the electroconductive properties of magnetorheological elastomers under the influence of magnetic field is brought in a number of publications by Biki I [7–11]. Our investigations of the magnetoactive, magnetorheological elastomers demonstrated that changes in the electroconductivity under the influence of magnetic field and mechanical force are characterized with a significant hysteresis.

2 Experimental Details

A series of experimental samples with the following compositions were prepared:

Magnetic filler—80 wt%, polymer matrix—20 wt%.

Sample 1. Magnetic filler: carbonyl Fe—50 wt%, carbonyl Ni—50 wt%.
Sample 2. Magnetic filler: carbonyl Fe—50 wt%, Fe–Nd–B alloy—50 wt%.

The compositions of Samples 3 and 4 are similar to those of Samples 1 and 2; however, particles of the magnetic filler had an orientation owing to the fact that during the process of preparation the samples were held in a magnetic field of 40 mT applied collinear with the direction of electroconductivity measurements to be made.

Fillers: metal Ni and the Fe–Nd–B alloy are introduced into the composition owing to their moderate magnetic and exhibiting good electroconductive features.

For measuring the electroconductive properties of the magnetic fillers, they were taken as pure powders. The specific resistivities of the powders pressed into pellets with a diameter and height of 5 and 3 mm, respectively, under a specific pressure of 0.1 MPa came up to 150 Ohm·m for carbonyl Fe, 1–10 Ohm·m for carbonyl Ni, and 2–3 Ohm·m for the Fe-Nd-B alloy.

The composite was prepared by the following technique. The initial components, being magnetic powders and liquid silicone rubber, were mixed and rubbed up in a 3-roll powder dispenser. After the introduction of a toughener the mixture was vacuumed for the removal of air bubbles from the sample. Then the mixture was poured out into a cast with a diameter and height of 12 and 3 mm, respectively, and after affixing aluminum-foil electrodes on top and bottom, the sample was placed into the oven for polymerization at 110 °C. A number of samples were polymerized in magnetic field directed perpendicularly to the electrodes and plane of the sample. The process of polymerization promotes the formation of a strong connection between the composite and electrode.

Figure 1 depicts the schemes of the preparation of samples of electroconductive composites out of (A) and in magnetic field (B).

For the investigation of the electroconductivity of the MAE under the influence of magnetic field the installation presented in Fig. 2 was assembled. MAE samples prepared with the electrodes affixed were placed in between the poles of the electromagnet creating a homogeneous field. The resistivity of the sample was measured by means of a type Metex M-3610D resistance meter or ABM-4403 multimeter. The solenoid coils were powered with a B1-21 power generating unit. The magnetic field between the poles of the electromagnet was measured with a 2TP-1p teslameter.

The device of the second type was used for registering rapidly running processes of changes in the electroconductivity followed by recording the electronic data with a computer.

3 Experimental Results and Discussions

The investigation of the dependency of the electric resistivity of the MAE placed in the magnetic field showed the existence of a strong influence of the field on the ability of the material to conduct electric current. A plane sample of type 1 was held between the poles of the electromagnet oriented so as to provide the maximal possible perpendicularity of the sample surface to the direction of the field, as is shown in Fig. 2. The electric resistivity—magnetic filed dependency found for the material is presented in Fig. 3. The

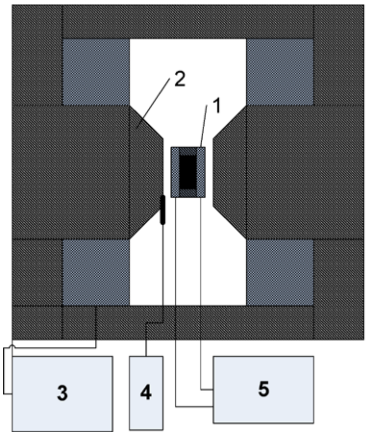

Fig. 2 Scheme of the installation for measuring the resistivity of MAE samples in magnetic field. 1—sample; 2—electromagnet; 3—power generating unit; 4—teslameter; 5—resistance meter

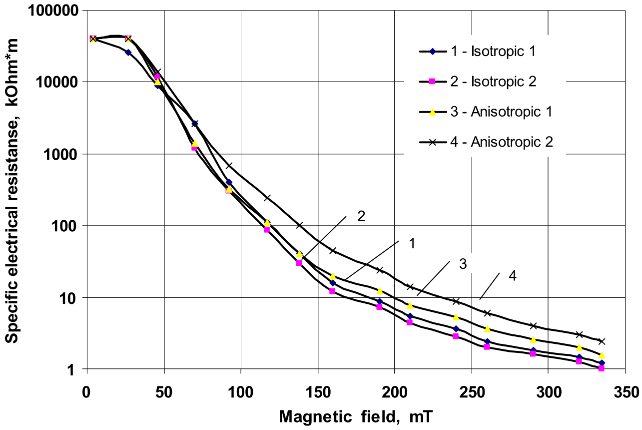

Fig. 3 Dependency of the specific electric resistivity of MAE samples on the strength of magnetic field

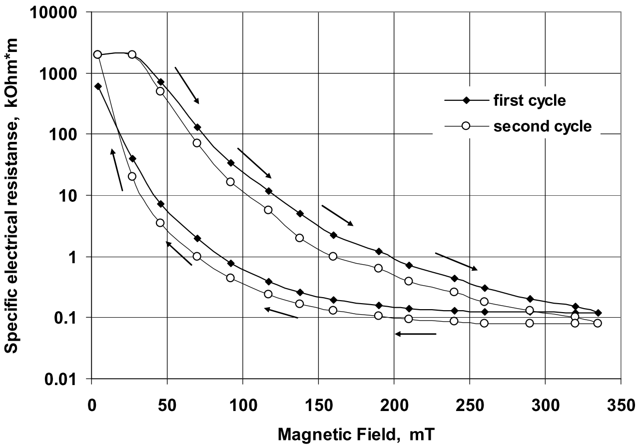

Fig. 4 Dependency of changes in the resistivity of the MAE on increasing and decreasing magnetic field. (The *arrows* along the curves depict the direction of changes in the field)

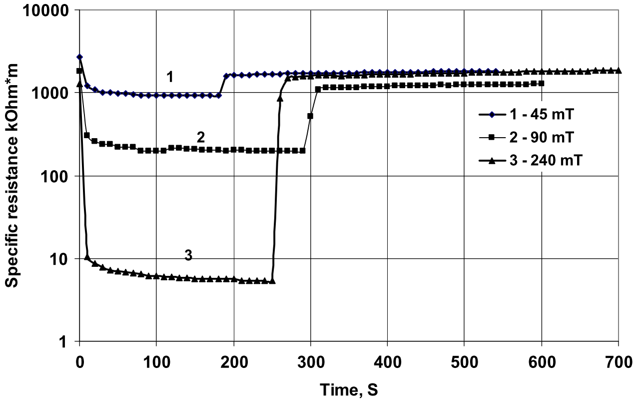

Fig. 5 Time-dependency of changes in the specific resistivity of the MAE with composition #2 in magnetic field changing in steps

strength of the magnetic field was increased in steps at an approximate exposure at every step for 10 seconds, as a result of which the resistivity value reached a level of 90 % saturation. As may be seen on Fig. 3, samples 1, 2, 3, and 4 corresponding to composition #1 demonstrate more or less uniform behavior.

An investigation of the character of changes in the specific resistivity of the material in increasing and decreasing magnetic fields was conducted for anisotropic sample 4 (Fig. 4). As is depicted in the drawing, the experiment revealed a significant hysteresis effect. During the diminishing of the strength of the field, a significant lagging of changes in the resistivity of the material was observed. Such a character of dependency was retained from cycle to cycle. As is possible, notice in Fig. 4 exhibiting two cycles only, the second cycle is somewhat shifted down. At thee same time, the third and following cycles exhibited practically no drifting and for this reason are not shown. Such a character of changes in the properties has already been observed in our earlier experiments during the investigation of the magnetostrictive effect and was interpreted as the specific nature of the restructuring of the composite in the field [4].

We observe the decreasing and increasing resistivity of the sample after the moment when the field is turned on and off, respectively (Fig. 5). After changing the magnetic filed in steps, the resistivity changes by 95 % of its equilibrium value practically momentarily, after which it the process of slow relaxation is observed.

The resistance of the samples changes under the influence of magnetic field due to an orientation acquired by the magnetic particles distributed in the polymer matrix. The elastic forces appearing inside the polymer matrix in response to the drifting of the particles of the filler are directed as to return the particles to the initial position. After the magnetic field is off, the resistivity of the sample grows back to the starting level.

Relative changes in the resistivity of the material in magnetic field changing in steps-is shown in Fig. 6.

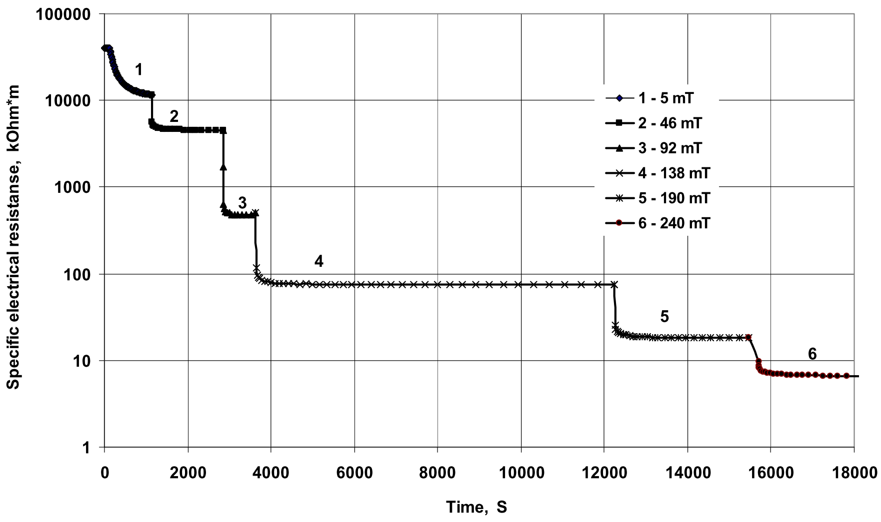

Fig. 6 Relative changes in the resistivity of the material in magnetic field changing in steps. The strength of the field is shown in the drawing

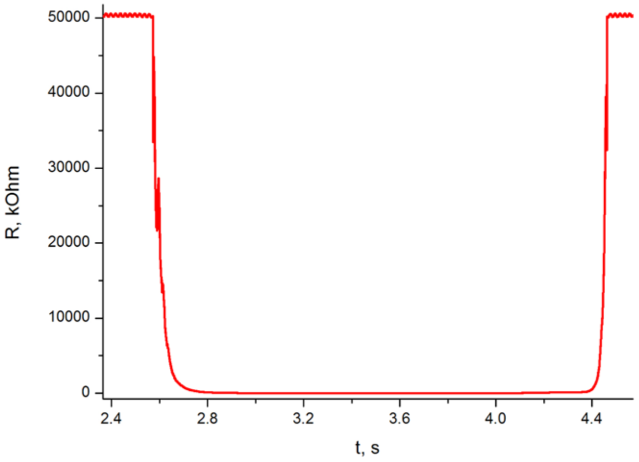

Fig. 7 Time-dependence of changes in the resistivity of the sample under the influence of mechanical shock

As may be seen in Fig. 6, the strength of the magnetic field applied does not affect the character of the dependencies of the resistivity on the value of the magnetic field: every step clearly exhibits a drastic decrease of the resistivity followed by a plateau where the system reaches stabilization. As may be noticed, after the field applied has been increased, the principal changes occur within 10–15 seconds.

As has been found out, under the influence of mechanical pressure the material exhibits changes in the electroconductivity, which means that the piezoresistive effect is observed (Fig. 7).

The resistance value depends on the value of the pressure and may decrease by approximately 4 orders. At a pressure of 0.1 MPa, the resistivity of the sample dropped from 20 MOhm to 2 kOhm. Change in the resistivity of the sample is connected with the decreasing of its thickness and reduction of distances separating the particles of the filler.

4 Conclusions

Thus, the material exhibits significant magneto- and piezoresistive effects.

Under the influence of magnetic field, the particles of the magnetic filler acquire a magnetic moment and begin to attract each other owing to dipole-dipole interaction, which causes the formation of chain-like structures growing through the sample along the direction of the applied field. Owing to the good conductivity possessed by the particles of the magnetic filler the resistivity of such structures drops. At the same time, mechanical pressure affects the sample in a similar way, for the distances separating the particles of the filler become shorter thus resulting in a reduction of the electric resistivity. Since the particles of the magnetic filler are distributed in the elastic matrix, the elimination of the influencing factor, being magnetic or mechanical, leads to the restoration of the resistivity observed initially.

This feature of the material might be used in the designing of magnetic-field sensors and strain gages.

The low price of the material and simplicity of devices utilizing it make it possible to create matrix structures to cover wide surfaces of buildings, bridges, etc. and monitor the whole face of the installation.

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