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VISCOELASTIC PROPERTIES OF MAGNETORHEOLOGICAL ELASTOMERS IN THE REGIME OF DYNAMIC DEFORMATION

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Using the original procedure of a "clamped-free" vibrating sandwich beam the dynamic characteristics (elastic modulus and loss factor) of a number of magnetorheological elastomers have been measured. The influence of such parameters as the type of carrying matrix, the size of ferromagnetic-filler particles, and the intensity of action by the external magnetic field has been evaluated.

Elastomers represent a new class of technological materials that are widely used in structures, devices, and instruments to reduce vibrations and noise. Current- and magnetoconducting surfaces [1], flexible permanent magnets [2], etc. are manufactured based on elastomers with embedded metallic particles. Great interest in creating piezomaterials and "intellectual" composites based on elastomers, which contain current- and magnetoconducting particles, has developed in recent times [3, 4]. There are good grounds to believe that such "controlled" elastomers are more functional than traditional ones and can provide the basis for creation of "intellectual" structures and materials capable of finding application in a wide range of industries.

In general form, an electro- and magnetorheological elastomer is a solid analog of an electro- and magnetorheological suspension, namely, natural or synthetic rubber (polymer) filled with micron-size current- or magnetoconducting particles. A certain amount of current- or magnetoconducting powder is introduced into the liquid rubber-like matrix. Next, such a system is placed in, respectively, a constant electric or magnetic field of prescribed intensity and orientation for the time of its solidification due to the evaporation of a solvent, if the matrix is a solution of natural or synthetic rubber, or due to the cross-linking of the polymer. The forces of dipole interaction between the particles induced by the field force them to align in chains oriented along the force lines of the magnetic field. The structures of filler particles, aligned, oriented, and fixed in such a manner in the rubber-like matrix, form an electro- and magnetorheological elastomer whose accumulation modulus is nonzero in the absence of the field, has anisotropy, and is sensitive to electric or magnetic fields. The experiments have shown that, owing to the stronger dipole–dipole interaction of the magnetic particles of the filler, magnetorheological elastomers are more efficient than electrorheological ones.

In particular, calculations and experiments confirm that when the magnetic field is switched on by the magnetic forces of interaction between the particles the accumulation modulus for such elastomers increases by 30–50% as compared to the values in the absence of the field. The optimum value of the volume fraction of the magnetic filler must be of the order of 27–30%. Furthermore, in the absence of the magnetic field the accumulation modulus of such an elastomer in the direction perpendicular to the chains which are oriented along the force lines of the magnetic field does not exceed its values for unoriented particles for the same values of the concentration [5].

Many versions of magnetorheological elastomers exist, which differ in composition and in the method of their production. There are anisotropic viscoelastic composites which are made up of micron-size particles of carbonyl iron, embedded in natural rubber, and have initially nonzero moduli of shear and accumulation, which sharply increase under the action of the magnetic field.

There are thermoplastic magnetorheological elastomers filled with submicron needle-shaped particles. Their mechanical properties and accumulation modulus substantially depend on the number, orientation, and temperature of such magnetic needles. Generating the microstresses between the particles by the external magnetic field, one can control and monitor the macrostresses in such an elastomer.

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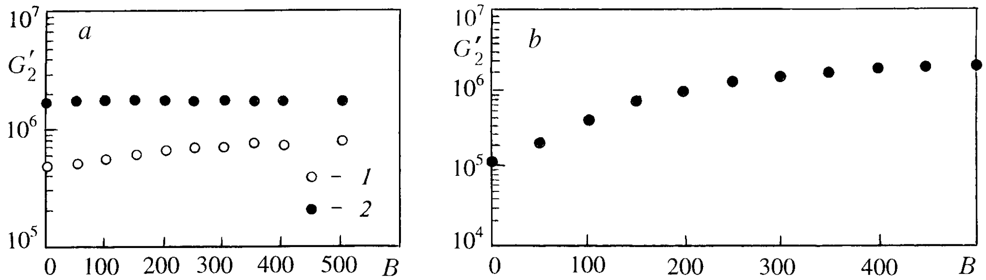

Fig. 1. Accumulation modulus of a gelatin-based magnetorheological elastomer (a) [1) unoriented layer and 2) oriented layer] and of an unoriented silicone-based magnetorheological elastomer (b) vs. magnetic field intensity.

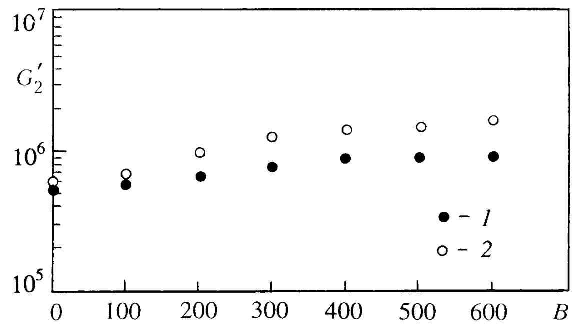

Fig. 2. Accumulation modulus of a magnetorheological elastomer vs. magnetic field intensity: 1) unoriented layer; 2) oriented layer; the size of filler particles is 3.5 μm.

The behavior of the adaptive structure, which represents a three-layered beam with the damping layer of elastomer between two nonmagnetic plates with one end of the beam being rigidly fixed — such a structure is called a "sandwich" — has been investigated using a standard procedure of measurement of the vibration–damping properties (loss factor η_2 and dynamic accumulation modulus G'_2) of composite materials in the form of cantilever beams in a wide range of frequencies and temperatures [6].

A distinctive feature of the present investigation was that instead of ordinary rubber or a magnetorheological suspension we used a magnetorheological elastomer as the damping layer; the elastic properties of the elastomer were controlled by a magnetic field. In addition to the necessity of complying with the basic requirements of the standard procedure, it was necessary to eliminate the influence of the magnetic field on the signals of sensors which drive and receive oscillations of the sandwich, to ensure the adhesion of the layer of elastomer to aluminum plates, and to solve a number of other problems. These problems were solved using special techniques partially described in [7], which enabled us to improve the standard procedure.

The basic quantity measured in the experiments was the *resonant frequency* of forced oscillations of a sandwich at the second mode f_{res} in the absence of a magnetic field ($B = 0$) and the shift of f_{res} under the action of a magnetic field on the sandwich ($B = 0$–600 mT). Next, from the formulas of [6] we calculated the basic dynamic characteristics: the accumulation modulus G'_2 and the loss factor η_2 of the damping layer of a magnetorheological elastomer and of the entire sandwich η.

On the basis of the relative simplicity of preparation of thermoplastic magnetorheological elastomers for calibration tests, we selected test specimens based on a 25% solution of gelatin and EW carbonyl iron (BASF, Germany) (10–25% by volume). The specimens, prepared in such a manner and heated to 30–35^{o}C, were poured into a sandwich mould and cooled to room temperature (~14–18^{o}C). Such specimens are considered to be unoriented, i.e., in the process of cooling, they are unaffected by a magnetic field and the particles of carbonyl iron are distributed in such a specimen randomly.

The oriented specimens were prepared similarly, but in the process of cooling we placed them in a magnetic field whose force lines were directed perpendicularly to the sandwich surface. Figure 1a gives the elastic moduli of

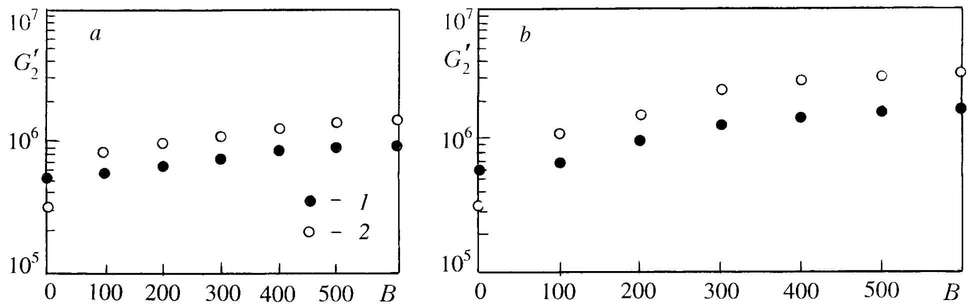

Fig. 3. Accumulation modulus of an unoriented formoplast-based magnetorheological elastomer (a) and of an oriented one (b) vs. magnetic field intensity: 1) particle diameter is 3.5 and 2) 13 μm.

oriented and unoriented magnetorheological elastomers; the loss factor of the entire sandwich and of the layer of the magnetorheological elastomer virtually remained constant, apparently, because of the insignificant influence of viscosity (as compared to elasticity) on the dynamic characteristics of the sandwich. Among the advantages of thermoelastic magnetorheological elastomers can be the simplicity of their manufacture and reversibility relative to temperature; the largest drawback of gelatin-based magnetorheological elastomers is their short service life, i.e., destruction with time.

The next investigated magnetorheological elastomer was a matrix of silicone rubber with the embedded particles of carbonyl iron of the same grade as in the previous specimen. The silicone rubber was initially dissolved in ethylacetate in the proportion 50/50. Then a powder of EW carbonyl iron (28% by volume), specially processed for better stability, was added to this solution with the lowest expenditure of time. The mixture was uniformly mixed in a mortar and poured into a rectangular organic-glass mould with sandwich parameters in length and width and an open upper surface for evaporation of the solvent. The thickness of the elastomer layer was monitored by glass calibration spheres 0.55 mm in diameter and was gained after several pourings of the dissolved elastomer to eliminate the formation of air bubbles in evaporation of the solvent if the layer turned out to be rather thick. Because of the distinctive features of this type of elastomer, the structure of the sandwich was substantially simplified and represented two aluminum plates between which the elastomer layer was found. In this variant, the main difficulty was associated with the creation of adhesion between the adjacent surfaces of the sandwich plates and the elastomer, which was attained by special treatment of the surfaces of these plates.

Figure 1b shows the accumulation modulus of such an unoriented magnetorheological elastomer as a function of the magnetic field intensity. As is seen, the curve has the character of saturation in the region of the field intensity of ~500 mT; the accumulation modulus increases by more than an order of magnitude.

In the next run of experiments, the object of investigation was a formoplast-based thermoelastomer distinguished by the relative simplicity of manufacture. Formoplast is a version of thermosensitive silicone rubber. As the magnetosensitive fillers, we used three fractions of a powder of EW carbonyl iron with a particle size of 3.5, 13, and 23 mm. The mixture with a certain proportion of the ground formoplast, the carbonyl-iron particles of a specified size, and glass calibrated spheres 0.55 mm in diameter (to monitor the thickness of the elastomer layer) was placed in a thermal chamber and was heated to a certain temperature. The melt was poured into a mould fixing the sandwich plates, and depending on the problem the mould was simply cooled (unoriented elastomer) or placed in the hot state in a magnetic field of specified strength and orientation for further cooling (oriented elastomer) during the specified time. Then the magnetorheological elastomers produced were tested according to the above procedure. From Fig. 2 it is seen in what manner the orientation of the filler particles influences the elasticity of such a magnetorheological elastomer: in the absence of the field, the difference is virtually unnoticeable, while for relatively high values of the field intensity the accumulation modulus of the oriented magnetorheological elastomer is nearly twice as large.

Figure 3 illustrates the substantial features of the influence of the filler-particle size and the magnetic field on the elasticity of a magnetorheological elastomer. In the absence of the field, the accumulation modulus of the magnetorheological elastomer with the larger size of the filler particles is nearly half as small as in the specimen with fine particles, while under the action of the field the situation is the reverse: with preservation of the saturation effect as the field increases the accumulation modulus of the magnetorheological elastomer with larger particles significantly exceeds the accumulation modulus of the magnetorheological elastomer with smaller particles.

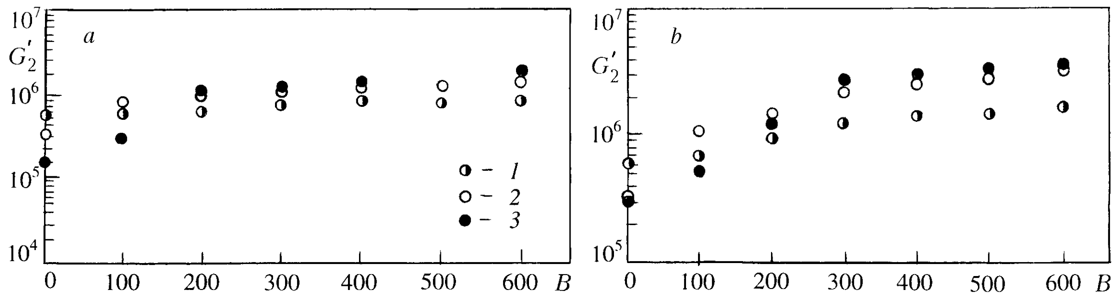

Fig. 4. Accumulation modulus of an unoriented layer of formoplast-based magnetorheological elastomer (a) and of an oriented one (b) vs. magnetic field intensity: 1) diameter of filler particles is 3.5, 2) 13, and 3) 23 μm.

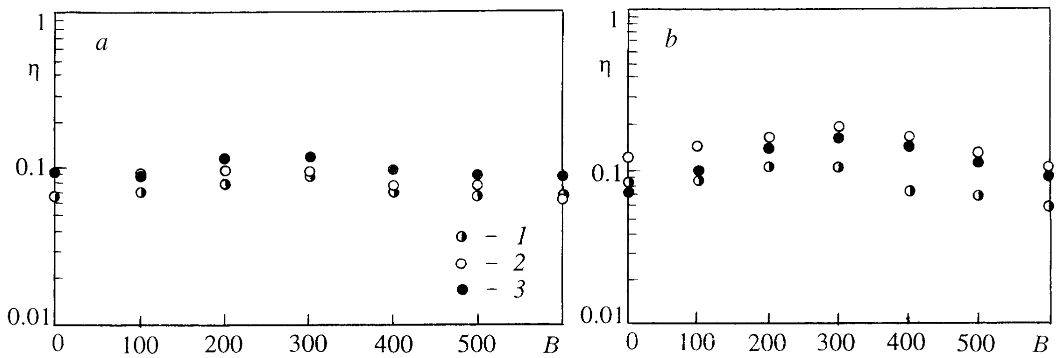

Fig. 5. Loss factor of the entire sandwich with the unoriented layer of formoplast-based magnetorheological elastomer (a) and with the oriented layer of elastomer (b) vs. magnetic field intensity: 1–3) notation is the same as in Fig. 4.

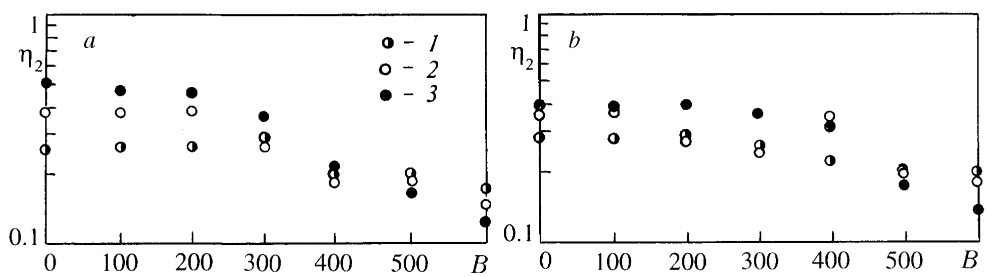

Fig. 6. Loss factor of an unoriented damping layer of formoplast-based magnetorheological elastomer (a) and of an oriented one (b) vs. magnetic field strength: 1–3) notation is the same as in Fig. 4.

The complete picture of influence of the size of filler particles (3.5, 13, and 23 μm), the character of the structure made of these particles, and the magnetic field intensity (0–600 mT) on the dynamic characteristics of the sandwich (accumulation modulus and loss factors of the damping layer of the magnetorheological elastomer and the entire sandwich) is illustrated by Figs. 4–6. We can unambiguously state that even in the case of the unoriented layer of magnetorheological elastomer under the action of a magnetic field, the larger the particles of a ferromagnetic filler are, the larger the accumulation modulus, i.e., the elasticity of the magnetorheological elastomer. The situation is the reverse in the absence of the field: the unoriented magnetorheological elastomer filled with larger particles is more plastic (Fig. 4a). Under the action of the magnetic field, the larger particles of the filler, aligning along the force lines of the field, form a more powerful internal structure and hence a more elastic magnetorheological elastomer (Fig. 4a), which is especially pronounced in the case of the magnetorheological elastomer oriented in the process of manufacture (Fig. 4b) where the accumulation modulus increases by more than an order of magnitude.

Traditionally, the loss factor of the entire sandwich with both the unoriented layer of magnetorheological elastomer and the oriented one remained virtually indifferent to a change in the magnetic field intensity (Fig. 5) because of the relatively small contribution of the viscous properties of the layer of magnetorheological elastomer to the dynamic characteristics of the entire sandwich.

On the other hand, the loss factor of the layer of the damping magnetorheological elastomer shows a marked decrease as both the magnetic field intensity increases and the filler-particle size increases. This dependence is more pronounced for the layer of the unoriented magnetorheological elastomer with the larger size of the particles (Fig. 6a) because of the absence, in them, of a rigid internal structure characteristic of oriented magnetorheological elastomers (Fig. 6b).

NOTATION

G_2', accumulation modulus of the magnetorheological elastomer, Pa; f_{res}, resonant frequency of the second mode of the sandwich, Hz; $\eta = \Delta f_2/f_2$, loss factor of the entire sandwich; η_2, shear loss factor of the magnetorheological elastomer; B, magnetic field intensity, mT.

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