Testing the magnetoactive elastomer sample for compression with the test machine

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Abstract. A sample of a magnetoactive silicone composite with ferromagnetic fillers is examined on a testing machine. The dependences of the change in the values of the moduli of longitudinal elasticity on deformation are plotted for various modes of compression of the sample. The characteristics of the linear and nonlinear dynamics of changes in the moduli of longitudinal elasticity are given as a function of the magnitudes of the deformations of the material during compression. Within the limits of deformation of the sample, which is 24% of its height, the moduli of longitudinal elasticity are linear. The nonlinear nature of the change in the compression modulus occurs when the sample is deformed over 40%. When the compression ratio of the sample was up to 72%, the compression modulus increased by a factor of 9 without the action of a magnetic field and by a factor of 22 under the action of a magnetic field. The influence of the magnetic field on the growth of the compression moduli with the increase in the compression force ranges is shown. The property of the material to self-healing ("shape memory") was established after testing in the mode of maximum compression of ultimate loads.

1. Introduction
Magnetoactive silicone composite materials belong to the developed and investigated new class of so-called intelligent materials that can significantly deform, change their physical parameters, shape and size, and restore their shape after removing the load. To expand the range of applications in various industries of industrial production of magnetoactive elastomers, comprehensive studies of both dynamic and static strength properties of the composite materials created are required. The performed dynamic tests showed a significant dependence of the created composite materials on the influence of the magnetic field [1-5]. It was found that the effect of a magnetic field can significantly, almost twofold, shift the resonance frequencies in the test materials. Magnetoactive elastomers are being investigated for systems of active vibration protection, where stringent requirements are required for the dynamic characteristics of the performed technological processes [6,7].

Various test methods are used to improve the technological process of developing magnetoactive, multicomposite materials with new dynamic properties. A number of test specimens were used to experimentally study the change in the elastic properties of magnetoactive elastomers under loading in various force modes of compression [8]. The characteristics of the change in the moduli of longitudinal elasticity (Young's modulus) are insufficiently studied. The characteristics of the modes of transition of linear change in elastic moduli to nonlinear ones at various values of deformation and corresponding to this compression force of the test material have not been sufficiently studied. There are no studies related to the self-healing of magnetoactive elastomers.
2. Problem statement

The purpose of these studies is to experimentally test a specimen for compression in various modes, to study the characteristics of changes in the moduli of longitudinal elasticity and, on the basis of the obtained experimental data, to improve the technology for the production of new materials of magnetoactive elastomers (MAE). The tests carried out on prototypes show a significant dependence of their dynamic properties on the effect of external magnetic fields. For further multifaceted studies, including in the field of changes in the dynamic properties of magnetoactive elastomers, it is necessary to know the ranges of characteristics of changes in the moduli of longitudinal elasticity in different modes of compression of samples of the materials created. The change in dynamic properties as a result of loading in various modes of compression of magnetoactive elastomers has not been adequately studied. There are no characteristics of the modes of transition of linear change in elastic moduli to nonlinear ones at different compression forces. An electromechanical testing machine is used to obtain information about the conditions and characteristics of the reversible and irreversible deformation of the sample, at various, including maximum and extreme, compression modes of the test sample.

3. Prototype testing machine

The sample was tested on an LFM-L-10 electromechanical testing machine (Walter + Bai AG, Switzerland), designed for physical and mechanical research of the newest materials being created. The test system is a modular design that can be equipped with grips, fixtures, extensometers, software, and other accessories. The machine is designed for compression, rupture, flexure, shear or peel tests and many other tests for various types of materials. Maximum loads from 10 kN (1 ton) and minimum loads 50 N (5 kilograms). Rigid composite modules with anodized frames are precision systems that combine high quality and small size. The backlash-free ball screw provides high loads, high positioning accuracy and repeatability. This design provides not only tensile and compression tests, but also the O test (quasi-cyclic loads). Backlash-free composite modules are driven by a servo motor through a digital controller. The LFM-L series incorporates the latest digital technology to ensure the accuracy and reproducibility of test results, and a software suite fully automates the test process.

Compression plates DP 10 were used as accessories; bottom plate with concentric circular grooves for centering the test piece; top plate - with tapered fit - for leveling. We tested samples made in the form of a cylinder: diameter and height, which were respectively 30 and 27 mm. Samples of magnetoactive elastomers were made using a special technology by adding particles of carbonyl iron and powdered iron to the silicone compound with a particle size from several microns to several tens of microns. It should be noted that this test sample differed in its elastic characteristics from the test samples presented in [8]. The speed is constant and the same for all tests - 5 mm/min. Data recording frequency - 20 Hz. No preloading (preloading) was applied.

4. Results of experimental tests of samples

As test modes, various criteria for specimen compression 10 mm, 20 mm and maximum compression up to 10 kN were chosen.

The starting position before starting the test is shown in figure. 1. A sample is set in the center of the lower plate, and the upper plate is brought to the upper surface of the sample until it touches. At the same time, it is controlled that the load is zero in the initial position. When testing with a magnet, a magnet is first installed on the bottom plate: shown in figure 2, and then a sample on it. The magnetic field on the test sample was created using a rectangular neodymium magnet with a surface magnetic induction of 1.7 kOe.
The characteristics of the change in the modulus of longitudinal elasticity (Young's modulus) during compression (hereinafter for brevity: the modulus of compression) of the test specimen were determined from the results of measuring the dependence of the force on deformation. Compression modulus - MPa, was calculated by the formula: $F/A \epsilon$, where $F$ is the force applied to the sample to obtain deformation under compression (Newton); $A$ is the initial cross-sectional area of the test piece (mm$^2$); $\epsilon$ - compression deformation (mm). Figures 3, 4 and 6 below show the graphs of the change in compression moduli (along the vertical axis in MPa) based on the results of measurements and processing of tests, depending on the degree of compression of the sample as a percentage of its initial height (along the horizontal axis Epsilon in%). The presented graphs show the dynamics of changes in both linear and nonlinear characteristics of compression moduli, characteristic of the test specimen, depending on the magnitude of its deformation in various limiting compression criteria or modes of movement of the upper plate of the electromechanical testing machine.

In the first test, the ultimate compression criterion was set at 10 mm, which was Epsilon 37% of the specimen height. In figure 3 a) and figure 3 b) shows the linear nature of the change in the compression modulus within the deformation of the sample constituting Epsilon 24% of its height. Within the specified limits of compression at Epsilon 24%, an increase in the compression modulus is observed when the sample is exposed to a magnetic field by a factor of almost 1.5 compared to its absence. With an increase from Epsilon 24% to Epsilon 40%, there is a smooth transition of the change in compression modulus to the nonlinear region. In the specified compression range from Epsilon 24% to Epsilon 40%, the compression modulus in the absence of exposure to a magnetic field increased 2.4 times, and when exposed to a magnetic field increased more than 4.3 times.
Subsequent tests show the resulting records meeting a compression limit of 20 mm and a compression ratio slightly exceeding 72% Epsilon of the specimen height. Figures 4 a) and 4 b) show the non-linear nature of the change in the modulus of compression within the specified limits of sample deformation, which constitute a compression ratio slightly exceeding Epsilon 72% of its height, respectively, without and with the effect of a magnetic field on the test sample.

**Figure 3.** Limits of linear characteristics of elastic modulus change.

**Figure 4.** Nonlinear nature of changes in the modulus of elasticity.

Figure 4 a) shows that under these test conditions, without the influence of a magnetic field, there is a nonlinear rise in the compression modulus from 0.005 MPa with a compression ratio in Epsilon of 40% to 0.045 MPa with a compression ratio slightly higher than Epsilon of 72%. In this case, the compression modulus increases by a factor of 9 times.
The effect of the magnetic field in the indicated test mode, shown in figure 4 b), led to a rise in the compression modulus from 0.014 MPa at a compression ratio in Epsilon of 40% to 0.314 MPa at a compression ratio slightly higher than Epsilon at 72%. In this case, the compression modulus increased by more than 22 times. Comparison of the recorded data shows that in the nonlinear section with a compression ratio in the Epsilon region of 72%, the impact on the sample with a magnetic field compared with its absence, the modulus led to an increase in the compression modulus by a factor of 7 times.

In the subsequent test modes, the maximum limiting compression modules for this testing machine were set up to 10 kN.

Figure 5 a) shows that when the sample receives the maximum deformation, it is compressed between the mounting plates in height up to several mm (“flattened”), or “stretched” in diameter, and at the same time it goes beyond the boundaries of the diameter of the plate in width.

Figure 5 b) shows the shape of the specimen after unloading with permanent deformation. Shown in Figure 5 b) residual, partially reversible deformation, preserved in the first moments after the removal of the load.

Figure 5 c) shows the restored shape of the specimen after an ultimate load of 10 kN.

![a) shape at ultimate compression. b) shape after unloading. c) recovered form.](image)

**Figure 5.** Forms of the specimen at ultimate compression, after removing the load and the restored form of the specimen.

Figure 6 shows the change in the boundaries of the compression modulus when tested up to the ultimate load of 10 kN.

![a) without magnetic field. b) with magnetic field.](image)

**Figure 6.** Change in modulus of elasticity at ultimate loads.
When tested close to the ultimate load of 10 kN, in the absence of exposure to the magnetic field, a sharp increase in the compression modulus begins in the region above Epsilon 90%. In this case, as can be seen from figure 6 a) the compression modulus increases to 14 MPa when Epsilon approaches 96%. The impact of the magnetic field on the test sample led to a smoother rise in the compression modulus in the Epsilon area of 80% and the compression modulus reached 14 MPa, also outside the Epsilon 96%.

Figure 6 a) shows that when tested at ultimate loads in compression ranges above Epsilon, 92% of the change in elastic modulus sharply increases from 2 MPa to 14 MPa. It can be seen from figure 6 b) that when a magnetic field is applied to the sample, there is a sharp increase in the compression modulus as well as without the action of a magnetic field from 2 MPa to 14 MPa, but it starts in a lower compression range with Epsilon 85%.

5. Discussion of the results

Test regimes with a specimen compression criterion of 10 mm and 20 mm had practically no effect on the appearance of the specimen. Loads over 20 mm led to the appearance of minor additional depressions - "discontinuities" of the material with a length of no more than 3-5 mm, oriented mainly along the generatrix lines of the cylinder. With insignificant compression deformations in the first two test modes discussed above, the test specimen has the ability to instantly restore its original shape after removing the load. There is practically no permanent deformation.

Figure 5 a) demonstrates the unique capabilities of this material (at extreme compression of 10 kN), namely: multiple, more than 500%, elastic stretching of the specimen in the transverse, horizontal direction with compression in height up to Epsilon 96%. The sample was maximally deformed in the longitudinal direction along the height and, accordingly, was stretched in the transverse direction (along the diameter) using a testing machine. Such a high percentage of elastic tension along the diameter of the test sample (more than 500%) shows the ultra-high flexibility of macromolecules between the molecular chains of the developed magnetoelastic material.

In figure 5 b) see the deformed shape of the specimen in the first moments, i.e. immediately after removal of the 10 kN load. The effect of plastic and partially reversible deformation is demonstrated. The sample, after more than 500% elastic tension in the transverse direction, is restored in this direction up to 200% - 300%, and along the height of the sample to values exceeding 10 mm.

Figure 5 c) shows an almost completely recovered shape after applying a load on a 10 kN testing machine. With such a significant load force on the sample, the original shape can be restored fairly quickly within a few seconds, when a slight deformation is applied in the form of a cyclic load along the lateral surface of the sample. The test sample demonstrates the "memory of the original shape" of the material after such significant loads and practically regains its original shape due to the application of a slight load.

6. Conclusions

When testing a sample of a magnetoactive elastomer, broad dynamic possibilities of changing the characteristics of the compression modulus without exposure to a magnetic field and under the influence of a magnetic field are shown. The boundaries of the location of linear and nonlinear sections of the compression modulus change in various modes of material deformation are given.

The obtained dependences of the linear and nonlinear characteristics of the change in the force characteristics of the compression modules, depending on the degree of deformation of the sample of the material under study, can be used for calculations in the design of micro damping devices, in the creation of magnetoactive propellers based on magnetoactive elastomers, as well as other products.

A unique possibility of self-restoration of the shape (size of the sample) after testing at a maximum load of 10 kN has been established. The test sample has a "shape memory effect" of the material under such significant, extreme loads, that is, it demonstrates the ability to completely restore its original shape.
In further tests, it is of great practical interest to determine the conditions of reversible and irreversible deformation of the sample and to study the effect of reverse creep.

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