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Magnetically Structured Composite Materials Based on Elastomeric Matrices with Different Viscoelastic Properties

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Abstract: Composite materials based on elastomeric matrices (sulphur-regulated chloroprene rubber - PCP and cold curing polydimethylsiloxane - SKTN-A) and magnetic fillers: hard magnetic (SmCo, NdFeB) and soft magnetic (natural magnetite Fe₃O₄, ZnNiCo-ferrite) in the concentration range of 30...100 mass parts per 100 mass parts of the elastomeric matrix have been obtained. The kinetics of curing of the considered elastomeric compositions was studied, on the basis of which the optimal molding modes were proposed. The samples were molded both in the presence of a magnetic field up to 0.3 T and without it. It has been established that the viscosity of the elastomeric matrix at various stages of curing significantly affects the microstructure and properties of the resulting composites. The electrophysical and magnetic properties of the samples have been studied. It is shown that the degree of structuring, which is directly related to the anisotropy of the characteristics under study, depends on the type of matrix used and decreases in the series SKTN-PCP. The studied materials can be used as "smart" materials controlled by an external influence (magnetic or electric field).

Keywords: elastomers, magnetically structured composites, functional material, electrophysical properties, magnetic properties

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1. INTRODUCTION

One of the conditions for the development of important science-intensive industries such as robotics, electronic computing systems, radio engineering in the era of active scientific and technological progress is the creation of new materials with special properties that can change nonlinearly under the influence of external factors such as electromagnetic field, magnetic and electric fields, mechanical action, etc. Such systems are called stimulus-sensitive or controlled materials. The names smart materials or metamaterials are also often found.

There are a mass examples of smart materials which distinguish feature consist of a special structure that allows to obtain systems with an “unexpected” property on the basis of known to science components [1-4]. Polymer composites that can change their characteristics under the action of an external magnetic field is paid much attention among smart materials [2,5,6]. Magnetostructured polymer materials, ferrofluids, magnetorheological fluids, magnetic gels, and magnetic elastomers or magnetoelastics are of great interest to high-tech industries and technology [5,6,7,8]. The latter are characterized by a number of interesting effects due to the controlled change in the Poisson's ratio [1], the modulus of elasticity [2,5,9,10], the anisotropy of elastic properties [5,6,10,11], the ability to control swelling [2,6], which provides a number of extraordinary applications of these materials in medicine, industry, and technology as artificial muscles [5, 6], energy storage and transfer systems [12], targeted drug delivery systems [2], selective sorbents [2], and much more [5,6,12]. In addition, research is being

carried out in the field of multisensitive magnetic elastomers [2], which can change their characteristics simultaneously under the influence of several external factors (magnetic field, temperature, pH of the medium). It is also important to note that the magnetic field is a convenient influencing factor for application in technology from the hardware point of view, which is an additional argument for the development and application of such systems.

One of the omissions of a number of research works in the field of creating magnetostructured materials is the insufficient attention paid to the technology of manufacturing such materials, the study of the dependence of the degree of structuring, the nature of the distribution of the magnetic filler in the polymer matrix, temperature, exposure time, and viscoelastic properties of the matrix used. A number of works can be single out [13,14,15] in which due attention was paid to these issues, but there are many examples [4,9–11] where the obtained structure is studied after the fact. To a greater extent, the properties of the resulting material are considered, rather than questions of the relationship, method of preparation and final properties. In this work, the selection of the most optimal way for obtaining samples characterized by the optimal degree of structuring was carried out on the basis of data from rotorless rheometry.

Based on the described earlier principles of structuring magnetic powders in an elastomeric matrix the maximum mobility of the magnetic filler at the initial stage of the process is necessary to be ensure.

This one is possible if two conditions are simultaneously observed - the minimum viscosity of the matrix and the magnetic field strength at a level that allows to overcome the resistance movement of the particles. In addition to these factors it can be assumed that the influence of the action of a magnetic field, particle size distribution, the volume content of the powder in matrix, particle morphology, specific surface, the nature of the physicochemical interaction between magnetic powder and matrix during structuring process should be also considered. These aspects of the structuring process were not affected in this work, however, in subsequent studies, it is planned to consider them and establish the relationship between the indicated parameters and the complex of electrophysical and magnetic characteristics of the obtained magnetoelastics.

2. MATERIALS, TECHNOLOGIES, EXPERIMENTAL TECHNIQUE

The following materials were used to prepare elastomeric composites:

- Sulfur-Modified Chloroprene Rubber Denka PS-40AH (Denka Company Limited, Japan), provided by OOO «ETS-M» with a Mooney viscosity of ML 1+4 (100°C) – 45. An oxide curing group consists from ZnO and MgO.
- Cold-curable silicone compound Viksint PK-68 (OOO PO Tekhnologiya-Plast) based on SKTN-A and a curing agent Catalyst No. 68 (tin diethyldicaprylate in a mixture of ethyl silicate-32 and toluene). Viscosity according to VZ1 viscometer (nozzle 5.4 mm) for SKTN-A is 90...150 s.
- Natural magnetite Fe_3O_4 – iron ore concentrate TU

07.10.10-006-00186803-2016 (hereinafter referred to as magnetite), provided by Lebedinsky Mining and Processing Plant JSC, Russia.

- ZnNiCo-ferrite obtained by ceramic technology, as well as SmCo and NdFeB powders purchased from company «Special Purity Substances».

The sample preparation process included two stages: mixing and subsequent curing, combined with the process of structuring the magnetic filler in the matrix under the action of an external magnetic field. The mixing step differed depending on the matrix. For composites based on chloroprene rubber mixing was carried out in two stages. In the first stage, the components of the formulation were mixed using a internal rubber mixer for 10 minutes at a temperature of 60°C at a rotor speed of 60 rpm. To improve the distribution of powdered components in the elastomeric matrix, the mixtures obtained at the first stage were processed on roll mills for 3-5 minutes.

For composites based on polydimethyl siloxane (SKTN-A), mixing was also carried out in two stages. At the first stage, magnetic filler was introduced into the liquid SKTN-A matrix and dispersed by stirring in a porcelain mortar for 5 minutes. In order to improve the distribution of powdered fillers in the matrix, the mixture obtained at the first stage was subjected to ultrasound in a bath with an ultrasonic generator GRAD 95-35 (OOO Grad-Technology, Russia) at a power of 220 W (ultrasonic frequency 35 kHz) and a temperature of 25-30°C within 10 minutes. Next, a curing agent (catalyst No. 68) was introduced into the resulting mixture in an

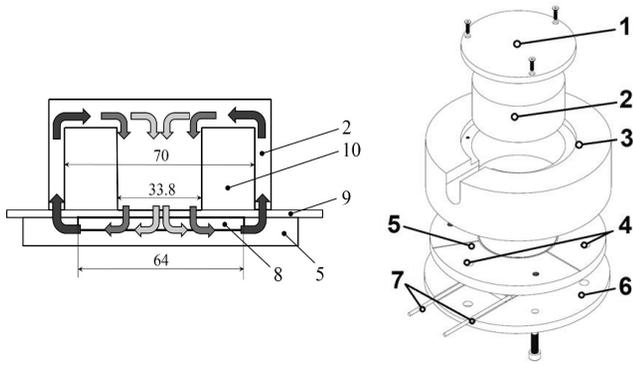


Fig. 1. Device for curing elastomeric materials in the presence of an external magnetic field.

amount of 10 phr on 100 phr SKTN-A and stirred for 1-2 minutes in a porcelain mortar.

Compositions based on chloroprene rubber, SKTN-A and magnetic fillers Fe_3O_4 , SmCo , NdFeB , ZnNiCo -ferrite were cured in a mold (**Fig. 1**), which allows to combine the processes of magnetic structuring and curing. The upper half-mould (3) is a cylinder made of non-magnetic material (duralumin D16), in the cavity of which an electromagnet (2) with windings (10) is fixed due a cover (1). The field of the electromagnet is 0.30 ± 0.02 T. The lower half-mold (5) is consist from forming part made of magnetically soft steel and has a forming cavity and flash grooves for removing excess material from the forming cavity and of heat-insulating platform (6) made of stainless steel. The heating of the mold is carried out by two heating elements (7), placed in the lower half-mold in such a way that the heating of the material in the mold cavity is carried out evenly. Technological gasket (9) with a thickness of 1.4 mm closes the forming cavity from above. The Atmega 328 on the Arduino Nano board is used as a microcontroller. The control of the electromagnet and the thermoregulation system

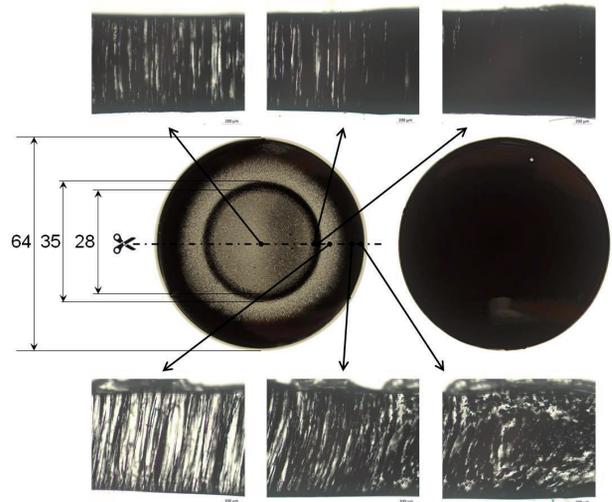


Fig. 2. Samples of elastomeric composites based on the SKTN-A matrix and Fe_3O_4 : structured on the left, unstructured on the right.

of the mold is carried out by sending commands from the PC through the COM-port.

The samples obtained as a result of curing are plane-parallel round plates with a diameter of 64 mm and a thickness of 1.1-1.4 mm (**Fig. 2**).

On Fig. 1 also shows a scheme of the magnetic flux through sample (8) and the magnetic circuit formed by the core of the electromagnet and the lower half-mould.

On Fig. 2 – micrographs of different regions of the diametrical section of a structured sample based on the SKTN-A matrix and Fe_3O_4 cured in a magnetic field. The unstructured sample cured without applying a magnetic field shown in Fig. 2 on the right.

The manufacturing process of magnetostructured samples included several stages. The first stage is the exposure of the material for 30 minutes at a temperature at which the matrix is characterized by a minimum viscosity, but the vulcanization processes, which limit the mobility of the magnetic filler in the elastomer matrix, are slowed down. These conditions ensure the optimal distribution of the magnetic powder

in the elastomeric matrix in accordance with the map of the distribution of the magnetic field strength in the volume of the mold cavity. The second stage includes heating at a rate of 1.5°C/min to the temperature at which the vulcanization processes for the given matrix proceed most efficiently. The third stage includes holding at the vulcanization temperature until the optimum vulcanization is reached, which is determined from the data of rotorless rheometry as the time to reach 90% of the difference between the maximum and minimum torque. Throughout the process, a constant magnetic field is maintained in the volume of the mold cavity.

Reference unstructured samples were made in the same mold under similar process conditions, excluding the first stage and in the absence of a magnetic field.

The study of the kinetics of the curing process of the elastomeric matrix was carried out using a dynamic moving die rheometer D-RPA 3000 (MonTech Werkstoffprüfmaschinen GmbH, Germany [16]). The measurements were carried out in the half-form oscillation mode. For chloroprene rubber-based elastomeric materials at a frequency of 1.67 Hz and an amplitude of 0.5° at initial stage temperatures ranging from 90 to 120°C and a final stage temperature of 150°C. For elastomeric materials based on the SKTN-A matrix at a frequency of 5.0 Hz, an amplitude of 0.167° at an initial stage temperature of 30°C and a final stage temperature of 50°C. The temperature increase between stages was carried out at a rate of 1.5°C/min.

The volume resistivity of the material plates $\rho_v, \Omega \cdot m$ was measured using an high resistance meter Agilent 4339B in a special

measuring cell 16008B, the measuring electrode diameter was 26 mm. The clamping device of the cell provides a tight contact between electrode and sample surface. The sample resistance was determined after holding it at a voltage of 100 V for 200 s. The thickness of the samples was measured with a micrometer type MK 0...25 mm at 6 points of the plate and then the average value was calculated. The calculation of the volume resistivity ρ_v was made according to the formula:

$$\rho_v = \frac{R \cdot S}{L},$$

where R – is measured sample resistivity, Ω ; S – is the surface area of the sample covered with the electrode, m^2 ; L – is the sample thickness, m .

The dielectric parameters were determined using an precision LCR Meter Agilent E4980A with a 16451B measuring cell, measuring electrode diameter 38 mm. The value of gap between the electrodes was determined using a built-in micrometer. The determination technique of relative dielectric permittivity ϵ is based on the dependence of the capacitance of a flat capacitor on the permittivity of the material between the electrodes [17]. The value of ϵ is calculated with formula:

$$\epsilon = \frac{C_x \cdot d}{\epsilon_0 \cdot S} = \frac{(C_x - C_p) \cdot d}{\epsilon_0 \cdot S},$$

where C_x – is the measured capacitance, F ; C_p – is the correction, consisting of the sum of the parasitic capacitance and the side capacitance of the measuring capacitor, F ; d – is the value of the gap between the electrodes, sample thickness, m ; ϵ_0 – is the dielectric constant equal to $8.854 \cdot 10^{-12}$ F/m; S – is the area of flat capacitor electrodes, m^2 .

The dielectric loss tangent $tg\delta$ of the studied composites is calculated with formula:

$$tg\delta_{\varepsilon} = tg\delta_x \cdot \frac{C_x}{C_x - C_p},$$

where $tg\delta_x$ – is the measured value of the dielectric loss tangent of the measuring capacitor.

The demagnetization curves were obtained using a VM-2K vibromagnetometer by measuring the magnetic moment of the test sample during its reciprocating motion in a constant magnetic field up to 10 kiloersted. The samples for measurements were discs 4 mm in diameter, cut from the central part of the composite plates (see Fig. 2). The control of the sample position in a constant magnetic field were carried out with turn indicator on the sample holder bar.

3. RESULTS AND DISCUSSION

The curing graphs of rubber compounds based on chloroprene rubber and various magnetic fillers at a concentration of 30 phr are shown on Fig. 3. The duration of the period which is characterized by a minimum torque (corresponding to the minimum viscosity of the system) is reduced with

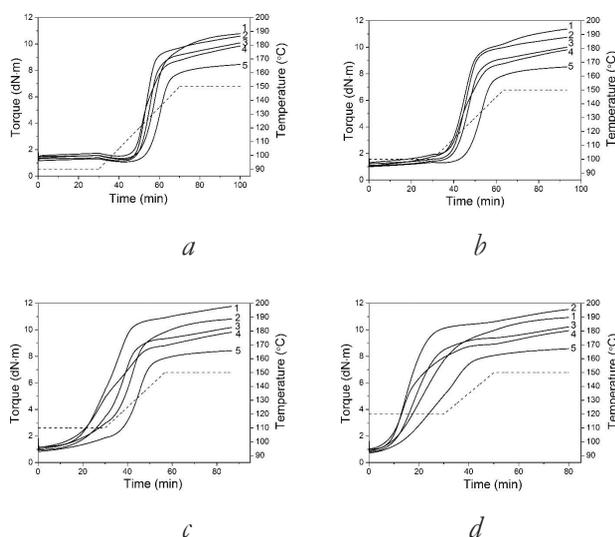


Fig. 3. Curing kinetics for rubber compounds based on chloroprene rubber.

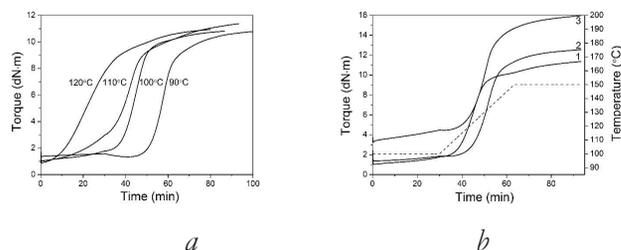


Fig. 4. Curing kinetics for rubber compounds based on chloroprene rubber and Fe_3O_4 .

an increase in the initial temperature of the process: a) 90°C; b) 100°C; c) 110°C; d) 120°C. The optimal mode in terms of the initial viscosity of the system and the duration of the structuring process for all studied compositions corresponds to an initial temperature of 100°C, which is clearly seen in Fig. 4a. The view of the cure graphs depends on the nature of the magnetic filler. Thus, in previous works, the influence of magnetite (curves 1 in Fig. 3) on the process of curing mixtures based on chloroprene rubber as an additional vulcanizing agent was demonstrated [18,19]. ZnNiCo ferrite behaves similarly (curves 2 in Fig. 3), which is probably due to the similarity of this compound in structure and physicochemical characteristics to magnetite. For other studied magnetic fillers (SmCo and NdFeB, curves 3, 4 in Fig. 3), an acceleration of the curing process is also observed compared to an unfilled matrix containing curing agents ZnO and MgO (curves 5 in Fig. 3).

The curing graphs for chloroprene rubber filled with magnetite (30 mass parts) depending on the initial temperature of the process (Fig. 4a) and on the concentration of the filler (Fig. 4b) are shown on Fig. 4. It has been established that the initial torque is growing up with increasing of the filler concentration (1 – 30 wt; 2 – 60 wt; 3 – 100

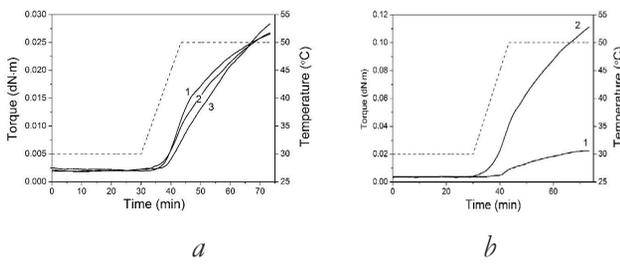


Fig. 5. Curing kinetics for SKTN-A.

wt), which complicates the process of particle structuring in a magnetic field.

The curing graphs of: a) SKTN-A and b) magnetoelasts based on it are shown on Fig. 5. Determination of rheokinetic characteristics for the liquid oligomeric matrix SKTN-A is difficult due to the weak response to sinusoidal deformations (3 – 1.67 Hz, 0.5°). SKTN-A was additionally tested in various modes with an increase in the oscillation frequency and a decrease in amplitude in accordance with the requirement of GOST R 54547-2011 (2 – 2.0 Hz, 0.5°) and a subsequent increase in the oscillation frequency (1 – 5.0 Hz, 0.167°) in order to search the most optimal ratio of measurement parameters for maximum response. The curing process of the liquid matrix SKTN-A occurs at relatively low temperatures – 30...50°C. In this regard, a significant effect of the type of magnetic filler on the kinetics of curing and on the initial viscosity of the system was not revealed. This is confirmed by curing graphs for SKTN-A filled with Fe₃O₄ in the amount: 1 – 30 phr, 2 – 100 phr are shown on Fig. 5b.

Determination of the rheokinetic parameters at different temperature conditions makes it possible to choose the optimal mode for manufacturing magnetostructured composites based on various elastomeric matrices and the optimal concentration of the magnetic

filler to obtain the most pronounced effect of structuring.

The results of measurements of electrophysical parameters and magnetic moment of the obtained samples of elastomeric composites with magnetic fillers are presented in Tables 1-8. We note the following: the increase in ε and tgδ, as well as the decrease in relatively unfilled matrices, are higher for the samples molded in a magnetic field. In this case, the relative changes are higher for composites based on the SKTN-A matrix.

Table 1 Composites based on chloroprene rubber and Fe₃O₄

Mat-rix	C, wp.	B, T	h, mm	ε·(tgδ)		ρ _v , Ω·m	M _{max} , mT	
				1 kHz	1MHz		Bottom	Top
PCP	0	0	1.24	6.0 (0.027)	5.2 (0.097)	(1.5±0.001)·10 ¹⁰	0	0
PCP	30	0	1.16	5.9 (0.014)	5.4 (0.077)	(5.7±0.09)·10 ⁹	0	0
PCP	30	0.3	1.14	8.0 (0.018)	7.0 (0.086)	(1.3±0.04)·10 ¹⁰	-0.07	0.16
PCP	60	0	1.15	6.4 (0.015)	5.9 (0.070)	(5.6±0.1)·10 ⁹	-	-
PCP	60	0.3	1.15	10.0 (0.024)	8.5 (0.079)	(7.1±0.2)·10 ⁹	-0.16	0.22
PCP	100	0	1.28	9.5 (0.030)	8.3 (0.084)	(4.0±0.07)·10 ⁹	0	0
PCP	100	0.3	1.26	17.3 (0.073)	12.9 (0.092)	(2.3±0.6)·10 ⁷	-0.20	0.19

Table 2 Composites based on SKTN-A and Fe₃O₄

Mat-rix	C, wp.	B, T	h, mm	ε·(tgδ)		ρ _v , Ω·m	M _{max} , mT	
				1 kHz	1MHz		Bottom	Top
CKTH-A	0	0	0.94	2.7 (0.001)	2.7 (0.001)	(3.9±10)·10 ¹³	0	0
CKTH-A	30	0	0.93	3.8 (0.011)	3.7 (0.005)	(2.4±3)·10 ⁹	0	0
CKTH-A	30	0.3	0.90	8.7 (0.079)	6.8 (0.029)	-	-0.15	0.33
CKTH-A	60	0	0.94	5.5 (0.028)	5.0 (0.013)	(2.4±0.3)·10 ¹²	-	-
CKTH-A	60	0.3	1.02	13.6 (0.098)	9.9 (0.040)	-	-0.17	0.20
CKTH-A	100	0	0.96	6.7 (0.027)	6.1 (0.013)	(1.3±0.1)·10 ¹²	-	-
CKTH-A	100	0.3	1.01	15.4 (0.091)	11.5 (0.026)	-	-0.19	0.19

Here: C (wp.) – filler concentration in weight parts; B(T) – magnetic field strength during vulcanization; h (mm) – the sample thickness; ε (tgδ) – permittivity (dielectric loss tangent) at frequencies of 1 kHz and 1 MHz; ρ_v (Ohm·m) – specific volume resistance; M_{max} (mT) – the maximum magnetic moment on each side of the sample, conditionally marked bottom and top.

Table 3

Composites based on chloroprene rubber and ZnNiCo-ferrite.

Mat- rix	C, wp.	B, T	h, mm	ε' (tg δ)		$\rho_V, \Omega \cdot m$	M_{max} mT	
				1 kHz	1MHz		Bottom	Top
PCP	0	0	1.24	6.0 (0.027)	5.2 (0.097)	$(1.5 \pm 0.001) \cdot 10^{10}$	0	0
PCP	30	0	1.21	5.5 (0.035)	4.6 (0.061)	$(9.0 \pm 0.006) \cdot 10^9$	0	0
PCP	30	0.3	1.16	7.3 (0.032)	5.9 (0.114)	$(8.2 \pm 0.1) \cdot 10^9$	0	0
PCP	60	0	1.13	7.7 (0.049)	5.9 (0.118)	$(4.9 \pm 0.07) \cdot 10^9$	-	-
PCP	60	0.3	1.18	8.4 (0.048)	6.1 (0.129)	$(4.2 \pm 0.05) \cdot 10^9$	0	0.08
PCP	100	0	1.12	9.6 (0.050)	6.7 (0.135)	$(1.1 \pm 0.03) \cdot 10^{10}$	-	-
PCP	100	0.3	1.14	10.1 (0.057)	6.8 (0.142)	$(1.1 \pm 0.03) \cdot 10^{10}$	-0.02	0.08

Table 4

Composites based on SKTN-A and ZnNiCo-ferrite.

Mat- rix	C, wp.	B, T	h, mm	ε' (tg δ)		$\rho_V, \Omega \cdot m$	M_{max} mT	
				1 kHz	1MHz		Bottom	Top
SKTN-A	0	0	0.94	2.7 (0.001)	2.7 (0.001)	$(3.9 \pm 10) \cdot 10^{13}$	0	0
SKTN-A	30	0	0.93	3.6 (0.025)	3.5 (0.048)	$(1.4 \pm 2) \cdot 10^{13}$	0	0
SKTN-A	30	0.3	0.75	3.5 (0.048)	2.5 (0.067)	$(8.6 \pm 0.6) \cdot 10^{10}$	0	0.11
SKTN-A	60	0	0.94	4.5 (0.038)	3.4 (0.061)	$(7.3 \pm 10) \cdot 10^{12}$	-	-
SKTN-A	60	0.3	0.97	8.7 (0.095)	4.5 (0.139)	$(1.2 \pm 0.2) \cdot 10^{11}$	-0.06	0.14
SKTN-A	100	0	0.93	5.0 (0.037)	3.8 (0.069)	$(6.4 \pm 10) \cdot 10^{12}$	-	-
SKTN-A	100	0.3	0.95	9.2 (0.087)	4.7 (0.151)	$(9.4 \pm 0.7) \cdot 10^{10}$	-0.05	0.11

Table 5

Composites based on chloroprene rubber and NdFeB.

Mat- rix	C, wp.	B, T	h, mm	ε' (tg δ)		$\rho_V, \Omega \cdot m$	M_{max} mT	
				1 kHz	1MHz		Bottom	Top
PCP	0	0	1.24	6.0 (0.027)	5.2 (0.097)	$(1.5 \pm 0.001) \cdot 10^{10}$	0	0
PCP	30	0	1.14	7.4 (0.023)	6.3 (0.102)	$(1.1 \pm 0.01) \cdot 10^{10}$	0	0
PCP	30	0.3	1.18	8.4 (0.036)	7.0 (0.099)	$(7.2 \pm 0.08) \cdot 10^9$	-0.10	0.18
PCP	60	0	1.15	7.8 (0.027)	6.6 (0.099)	$(1.8 \pm 0.04) \cdot 10^{10}$	-	-
PCP	60	0.3	1.16	8.6 (0.034)	7.3 (0.082)	$(9.7 \pm 0.2) \cdot 10^9$	-0.19	0.21
PCP	100	0	1.17	7.2 (0.023)	6.4 (0.072)	$(2.1 \pm 0.2) \cdot 10^{10}$	0	0
PCP	100	0.3	1.17	9.2 (0.032)	8.0 (0.064)	$(1.6 \pm 0.6) \cdot 10^{10}$	-0.38	0.36

Table 6

Composites based on SKTN-A and NdFeB.

Mat- rix	C, wp.	B, T	h, mm	ε' (tg δ)		$\rho_V, \Omega \cdot m$	M_{max} mT	
				1 kHz	1MHz		Bottom	Top
SKTN-A	0	0	0.94	2.7 (0.001)	2.7 (0.001)	$(3.9 \pm 10) \cdot 10^{13}$	0	0
SKTN-A	30	0	0.92	3.6 (0.009)	3.5 (0.002)	$(4.5 \pm 5) \cdot 10^{13}$	0	0
SKTN-A	30	0.3	0.93	5.0 (0.037)	4.6 (0.008)	$(1.1 \pm 0.02) \cdot 10^{10}$	-0.07	0.16

Table 6

Composites based on SKTN-A and NdFeB.

SKTN-A	60	0	0.89	3.7 (0.012)	3.6 (0.003)	$(2.0 \pm 0.8) \cdot 10^{13}$	-	-
SKTN-A	60	0.3	0.94	6.6 (0.040)	6.1 (0.009)	$(3.4 \pm 0.07) \cdot 10^{10}$	-0.16	0.22
SKTN-A	100	0	0.95	4.1 (0.016)	4.9 (0.004)	$(1.2 \pm 0.2) \cdot 10^{13}$	0	0
SKTN-A	100	0.3	0.97	7.8 (0.041)	7.1 (0.009)	$(1.5 \pm 0.04) \cdot 10^{10}$	-0.20	0.19

Table 7

Composites based on chloroprene rubber and SmCo.

Mat- rix	C, wp.	B, T	h, mm	ε' (tg δ)		$\rho_V, \Omega \cdot m$	M_{max} mT	
				1 kHz	1MHz		Bottom	Top
PCP	0	0	1.24	6.0 (0.027)	5.2 (0.097)	$(1.5 \pm 0.001) \cdot 10^{10}$	0	0
PCP	30	0	1.28	6.5 (0.023)	5.7 (0.090)	$(8.2 \pm 2) \cdot 10^{10}$	-0.11	0.16
PCP	30	0.3	1.26	17.3 (0.028)	12.9 (0.101)	$(2.7 \pm 0.03) \cdot 10^9$	-0.09	0.24
PCP	60	0	1.32	5.8 (0.018)	5.2 (0.080)	$(4.2 \pm 0.03) \cdot 10^9$	-	-
PCP	60	0.3	1.33	6.0 (0.018)	5.4 (0.078)	$(3.1 \pm 0.02) \cdot 10^9$	-0.19	0.19
PCP	100	0	1.41	6.6 (0.024)	6.0 (0.067)	$(3.9 \pm 0.05) \cdot 10^9$	-	-
PCP	100	0.3	1.38	9.5 (0.027)	8.4 (0.073)	$(3.0 \pm 0.4) \cdot 10^9$	-0.68	0.58

Table 8

Composites based on SKTN-A and SmCo.

Mat- rix	C, wp.	B, T	h, mm	ε' (tg δ)		$\rho_V, \Omega \cdot m$	M_{max} mT	
				1 kHz	1MHz		Bottom	Top
SKTN-A	0	0	0.94	2.7 (0.001)	2.7 (0.001)	$(3.9 \pm 10) \cdot 10^{13}$	0	0
SKTN-A	30	0	0.94	3.2 (0.003)	3.2 (0.001)	$(2.4 \pm 7) \cdot 10^{13}$	0	0
SKTN-A	30	0.3	0.95	5.4 (0.011)	5.2 (0.004)	-	-1.35	1.59
SKTN-A	60	0	0.94	3.9 (0.004)	3.8 (0.002)	$(6.0 \pm 7) \cdot 10^{12}$	-	-
SKTN-A	60	0.3	0.93	4.4 (0.006)	4.3 (0.003)	$(4.5 \pm 2) \cdot 10^{11}$	-0.43	0.49
SKTN-A	100	0	0.97	9.5 (0.008)	8.3 (0.004)	$(2.4 \pm 10) \cdot 10^{13}$	-	-
SKTN-A	100	0.3	0.97	17.3 (0.013)	12.9 (0.006)	-	-1.62	1.03

The characteristic magnetic profiles of the samples: a) 30 phr Fe₃O₄ in SKTN-A matrix, unstructured; b) 100 phr SmCo in chloroprene rubber matrix, structured; c) and d) 100 phr SmCo in SKTN-A matrix, structured, are shown on **Fig. 6**. Profiles a) and b) depicted double-sided, c) and d) depicted separate for each side of the sample. The value of the vertical axis in the figure is the magnetic moment of the sample part with the X and Y coordinates

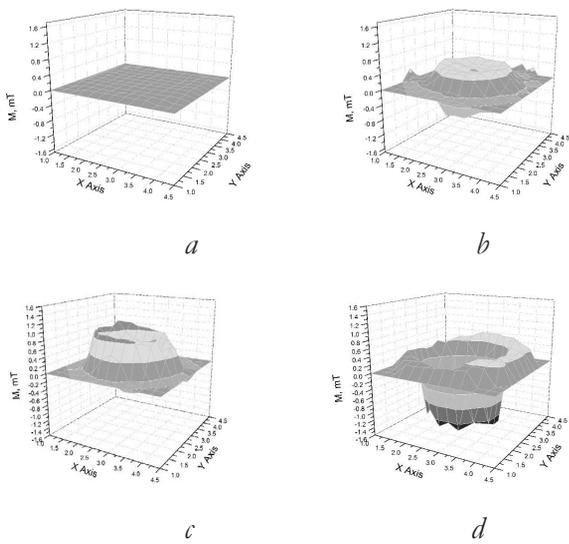


Fig. 6. Magnetic profiles of the samples.

(the maximum value along the axis is ± 1.6 mT). The magnetic moment was measured with a Mayak-3M Teslameter axial Hall sensor with a step of 5 mm along the X and Y axes.

The magnetic profiles of the samples demonstrate the degree of magnetic ordering of the filler in the elastomeric composite. More detailed information about the magnetic properties of the magnetostructured and unstructured samples can be obtained by magnetometric methods.

The array of demagnetization curves for composites was obtained according to the scheme shown in Fig. 7. The measurements were carried out in two

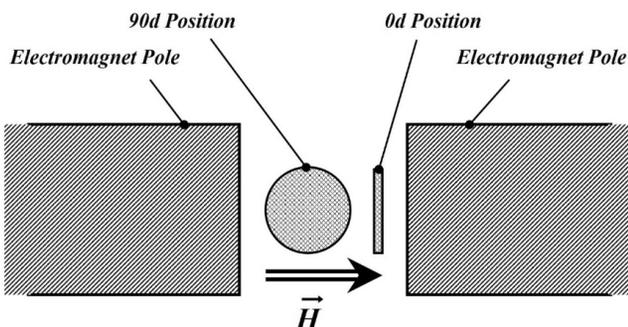


Fig. 7. Scheme for obtaining families of demagnetization curves.

positions of the sample plane: parallel (position 90d on the scale of the turn indicator) and perpendicular (position 0d on the scale of the turn indicator) to the magnetic field. The rotation of the sample relative to the direction of the constant magnetic field in the vibromagnetometer allows estimating the degree of magnetic anisotropy of the composite. Samples with a filler content of 30 phr were chosen for research. Higher concentrations do not allow to obtain high-quality (with saturation) demagnetization curves for all samples. Curve designations on Fig. 8-11 are following: EM0-0d, EM0-90d - sample cured in the absence of a magnetic field, orientation in the perpendicular and parallel directions, respectively; EM1-0d, EM1-90d – magnetically cured sample, orientation in perpendicular and parallel directions, respectively.

The demagnetization curves of the samples are shown in Fig. 8-11. In all figures a) and b) is the chloroprene rubber matrix, c) and d) is the SKTN-A matrix.

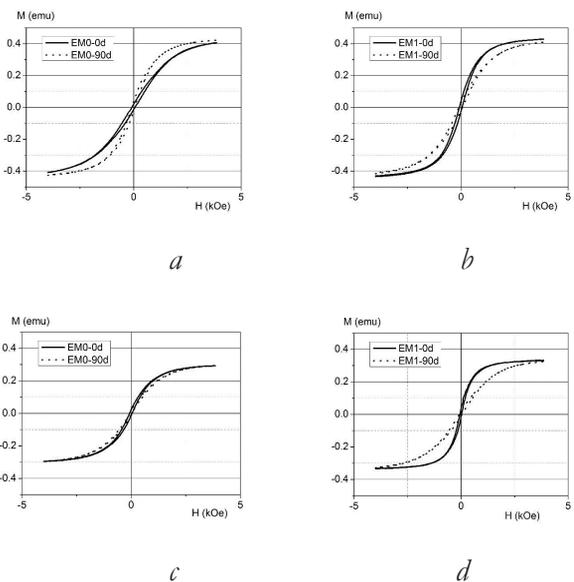


Fig. 8. Demagnetization curves for composites based on Fe_3O_4 .

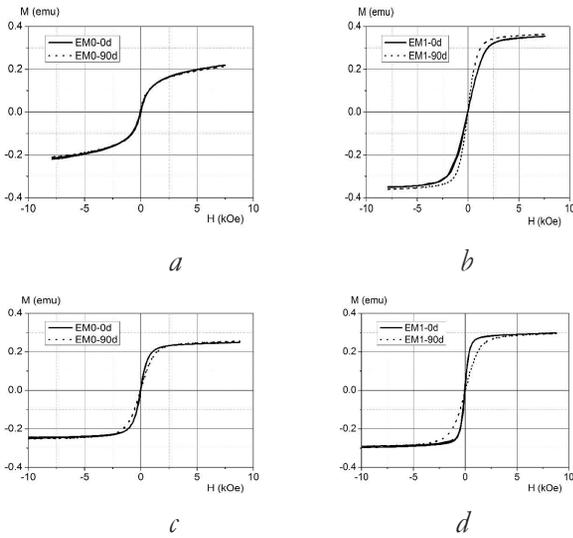


Fig. 9. Demagnetization curves for composites based on ZnNiCo-ferrite.

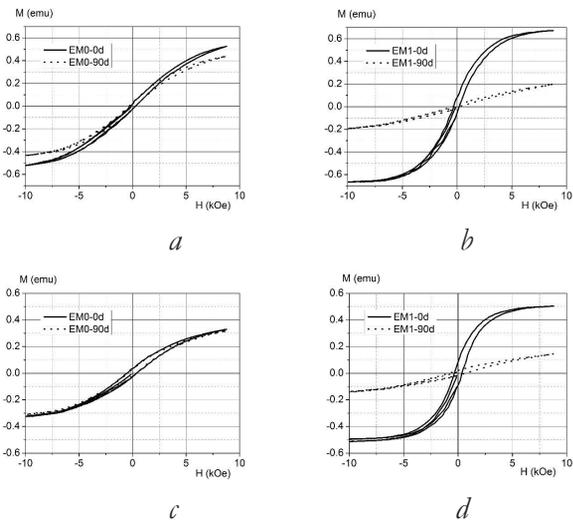


Fig. 10. Demagnetization curves for composites based on NdFeB.

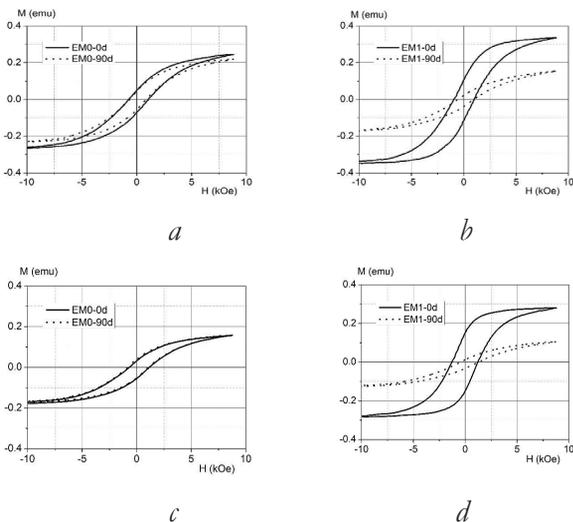


Fig. 11. Demagnetization curves for composites based on SmCo.

Summarizing the obtained magnetometric data, we can draw the following conclusions:

- magnetostructured samples (with the exception of chloroprene rubber - Fe_3O_4) have a pronounced anisotropy of magnetic susceptibility relative to the direction of the external magnetic field;
- the degree of anisotropy is higher for the SKTN-A matrix than for chloroprene rubber;
- the magnetic moment in a field of more than 4 kOe is higher for composites, both structured and unstructured, in the case of a chloroprene rubber matrix;
- for composites based on hard-magnetic fillers, the anisotropy fields in both matrices exceed 1 T.

4. CONCLUSION

In this work, the issues of developing technology and creating magnetoelasts with specified electrophysical, magnetic, stress-strain properties, techniques for controlling and detecting the nature of the distribution of a magnetic filler in an elastomer matrix depending on the production mode are considered.

Techniques for evaluating the most optimal mode of structuring magnetoelasts by analyzing the kinetics of the curing process in various temperatures have been developed.

It has been shown that, the content of the magnetic filler less effect on the viscoelastic characteristics of compositions at the initial stage of the process of manufacturing magnetostructured materials for compositions based on a liquid matrix SKTN-A than on chloroprene rubber.

Magnetically structured composites based on two elastomeric matrices, differing

in terms of the principle of curing, stress-strain properties, and a amount of hard and soft-magnetic fillers have been obtained and studied.

It has been shown that magnetoelasts based on chloroprene rubber and SKTN-A matrices have anisotropy of electrical and magnetic properties. The relationship between this anisotropy and the composition of the magnetoelasts and the parameters of its manufacturing process has been established.

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