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MAGNETIC ELASTOMERS BASED ON NANOSTRUCTURAL RE-3d-METAL-BORON AND IRON POWDER FILLERS WITH IMPRUVED ATTRACTION FORCE TO FERROMAGNETIC BODIES

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Abstract

In this work the magnetic and mechanical characteristics of magnetic elastomers named as hard and soft magnetic rubbers (HMR and SMR respectively) based on chloroprene, isoprene and butadiene-acrylonitrile rubber binders and nanostructural Rare-Earth-3d-Metal-Boron (MQP-B brand) and nanosized α-Fe powder fillers have been studied in details, particularly their ability to be attracted ("adhered") by ferromagnetic media, caused by the forces of magnetostatic interaction.

Experimentally, the dependences of magnetic-force parameter – specific attraction force (F) of HMR to the surface of a steel sheet on: a) filler concentration; b) HMR thickness; c) magnetic poles density (number); d) SMR thickness closing the back magnetic poles on HMR surface; e) air gap width between HMR and steel sheet surfaces have been inferred. As the final result, the HMR samples with F= 0.3-0.4 kg/cm^2 at the thickness of 1.5-2.0 mm have been manufactured.

Key words: *hard magnetic rubber, soft magnetic rubber, magnetic elastomers, Nd-Fe-B type nanostructural magnetic powder, specific magnetic attraction force.*

1. INTRODUCTION

In few past years due to the fast development of nanotechnologies nanocrystalline and nanosized systems are widely introduced into traditional fields of application and create new ones at the consumer market of functional materials. The separate place among them belongs to magnetic materials based on iron and nanostructural Rare-Earth alloys with iron and boron, which possess extremely high values of saturation magnetization (M_s), intrinsic coercivity (H_c) and maximal magnetic energy product $(BH)_{max}$ (Bushow et al. 1988).

For now the application of these materials as fillers for polymeric composites is not reported in literature. Meanwhile, such composites, which may be defined as "magnetic rubbers" or "magnetic rubber materials" (MRM) might find wide applications provided appropriate stability of their physical-chemical properties. For instance, practically advantageous are MRM made in form of thin elastic sheets with high magnetic attraction force (F) to ferromagnetic bodies. It is clear *a priori* that the value of F is proportional to the magnetic energy stored in MRM, which in turn depends on the magnetic characteristics of the filler, its content in composite, the degree of magnetization of MRM, and the configuration of magnetic poles ("magnetic picture") created on the surface of MRM sheet.

Therefore the objective of the present study was to prepare magnetic rubber material based on industrially available rubbers filled with soft magnetic powder (α –Fe) and hard magnetic powder

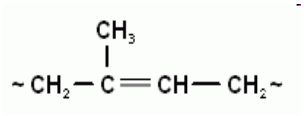
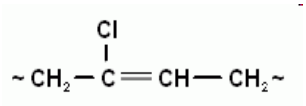
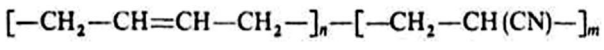
(nanostructured rare-earth-3d-metal-boron alloy), to characterize its physics-chemical and magnetic properties, and to explore the possibility of manufacturing thin elastic sheets with high attraction force to ferromagnetic bodies.

2. EXPERIMENTAL

Comercial rubbers: polyisoprene (SKI-3, GOST14925-79), polychloroprene (PCP, LANXESS), and copoly(butadiene-18%-nitrile) (CKN-18, TU 38.103488-89), were used as polymer binders for MRM. The molecular characteristics of polymers are given in Table 1.

The following magnetic fillers were used in composites with these binders: nanostructured hard magnetic powder MQP-B (MAGNEQUENCH Int.), produced by extra fast quenching of Nd-Fe-Co-B alloy and soft magnetic iron nanopowder produced by the electric explosion of iron wire in argon. Specific surface area of these powders was determined by low temperature nitrogen adsorption (BET) (Greg S. 1984) using vapor sorption analyzer TriStar3020 (Micromeritics). SEM micrographs, which present filler particle morphology and size (Figure 1) were obtained using Karl-Zeiss LEO982. The properties of magnetic fillers are given in Table 2. Magnetic rubber composites SKI-3/MQP-B, PCP/MQP-B, SKI-3/nano-Fe, SKN-18/nano-Fe were prepared according to the following: 40 mL of 5% solution of rubber binder in mixed solvent toluene/ethylacetate (1:3) were homogenized with 0.04 g of sulfur, 0.03 g of accelerator

Table 1. Characteristics of polymeric binders

Polymer type	Monomer chemical structure	Molecular mass M_w	d, g/cm^3
SKI-3		$12*10^5$	0,92
PCP		$4*10^5$	1,15
SKN-18		$3*10^5$	0,94

sulfeneamide C, and 0.03 g of stearic acid. This solution was mixed with weighted portions of magnetic powders to provide 10, 25, 50, 75, 90% (mass) of filler in final magnetic rubber composition. Dispersion of filler in binder solution was provided by 10 min sonification of the

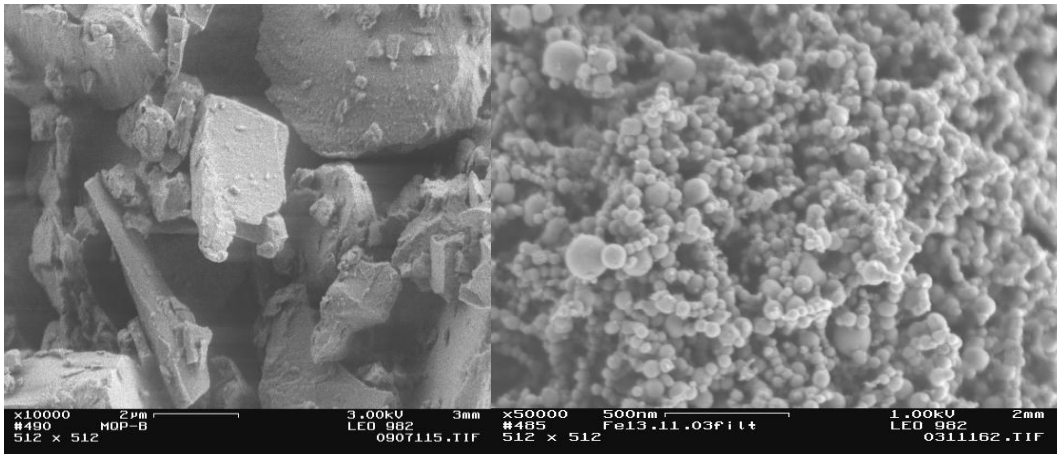


Figure 1. SEM photographs of MQP-B (left) and nano- Fe powders (right) used as rubber fillers

Table 2. Some characteristics of used powder fillers

Filler	Density, g/sm^3	Typical size (SEM)	Shape	S_{BET}, m^2/g	B_r, kGs	H_c,kOe
MQP-B	7,55	0,5 – 10 µm	Irregular polygrains	0,16	8500*	8,96
nano-Fe	7,87	10 – 100 nm	Sphere	9,35	800*	0,2

(*) – the value of induction is calculated based on the specific residual magnetization in zero field.

mixture in Cole-Palmer CPX750 processor. To prevent overheating the treatment was made by alternating 10 sec pulses and pauses. The film of magnetic rubber composition was prepared by casting the suspension onto PTFE surface. The solvent was removed in vacuum at 50°C. The raw composites were cured in thermal press at 2 atm: SKI-3 composites at 135 °C for 40 min, PCP composites at 143 °C for 20 min, SKN-18 composites at 150 °C for 50 min. The samples were made as 2 mm thick sheets for mechanical studies and 1-3 mm thick 28 mm diameter disks for specific attraction force (F) measurements. Double-layered MRMs, with magnetically hard and soft layers were made by duplication of cast composition films and their co-curing according afore-mentioned regimes.

Magnetic properties of cured MRMs were studied using vibrating sample magnetometer VM-112. Magnetic field specific magnetization dependencies ($m=f(H_e)$) have been measured in the external magnetic field range $H_e = \pm 15$ kOe, with the error ±3%. From these data the values of residual specific magnetization (m_r), residual induction (remanence) (B_r) and intrinsic coercivity (H_c) of initial filler powders and manufactured MRMs were determined. Mechanical study of MRMs was performed using bench-top mechanical tester RZM-3. Stress-strain plots up to break were obtained at 70 mm/min elongation rate at ambient conditions. Stress-at-break, breaking strain, and modulus at 20% elongation were measured with 4% accuracy. Attraction force of MRM to the 10 mm steel plate was measured by lab-modified dynamometer.

3.RESULTS AND DISCUSSION

3.1 Magnetic and mechanical properties of magnetic rubbers

Figure 2 presents demagnetization curves m = f(H_e) for MRM samples with 50% filler content previously magnetized in external field H_e=+15 kOe. The plots for the samples with other filler content look alike. Based on the value of the residual specific magnetization m_r and the density of compositions ρ the values of the residual magnetic induction B_r were calculated.

The value of m_r is in general the function of the magnetization of the filler and its content in the composition. The specific magnetization of MRM filled with nano-Fe in H_e=+15 kOe field is approximately 1.5 times higher than that for MRM filled with MQP-B at the same filler content. It stems from the higher value of saturation magnetization of nano-Fe as compared to that of MQP-B (Table 2)

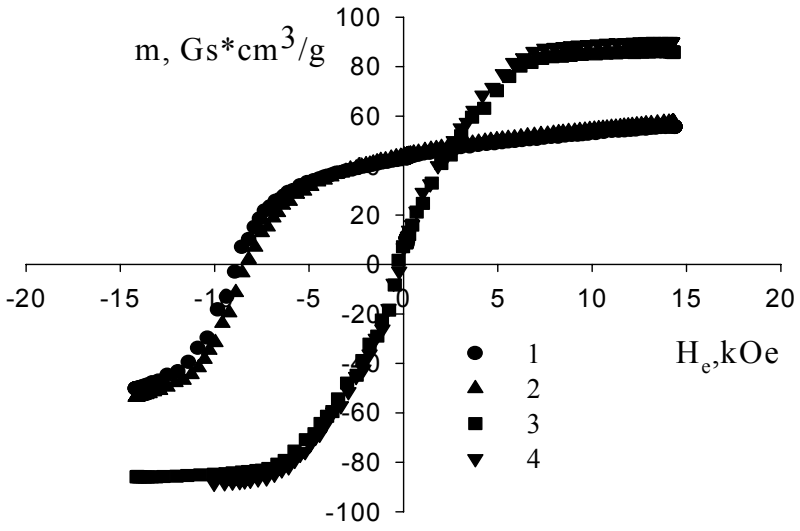


Figure 2. Demagnetization curves for MRM with 50% (mass) of magnetic filler for compositions: 1 - SKI-3/MQP-B, 2 - PCP/MQP-B, 3 - SKI-3/nano Fe, 4 - SKN-18/nano-Fe.

Figure 3 presents the dependence of the remanence (B_r) on the volume fraction of magnetic filler in the composition (c). One can see that B_r linearly increases with the volume fraction of the filler in polymer matrix. MRMs filled with MQP-B show higher B_r values than MRMs with nano-Fe in the entire range of filler content. Points, which correspond to compositions with different rubber binders, fit well the same linear regression. It means that remanence does not depend on the type of rubber binder but is exclusively the function of the type of magnetic filler and its content in MRM.

The dependence of intrinsic coercivity of MRM on the filler volume fraction (H_c=f(c)) is presented in Figure 4. Unlike B_r discussed above intrinsic coercivity of MRM non-linearly depends on c□□indicated that polymeric matrix influences H_c. Dependences H_c=f(c) for hard and soft composites are different. In the case of MRM filled with magnetically soft nano-Fe H_c values are low (0.2-0.4

kOe) and decrease with the filler content. The strongest changes correspond to the filler content up to 25%. At higher filler content intrinsic

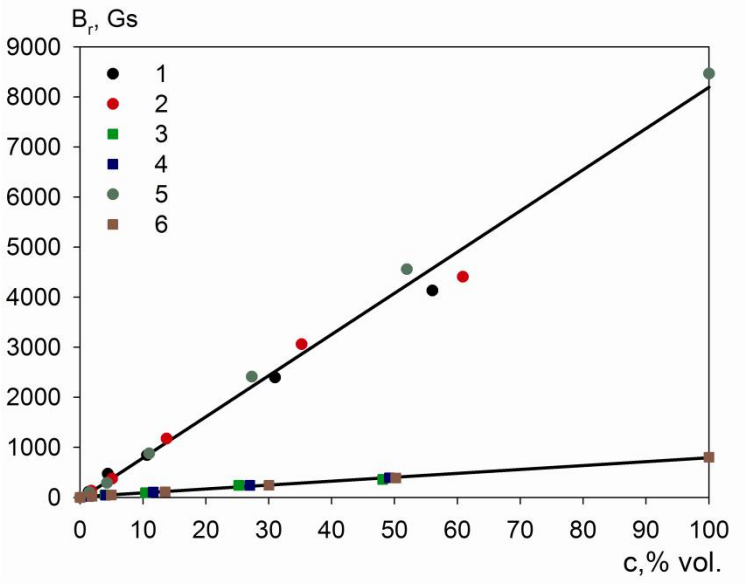


Figure 3. MRM remanence dependencies on the volume concentration of magnetic filler for the systems: 1-SKI-3/MQP-B, 2-PCP/MQP-B, 3-SKI-3/nano-Fe, 4-SKN-18/nano-Fe.

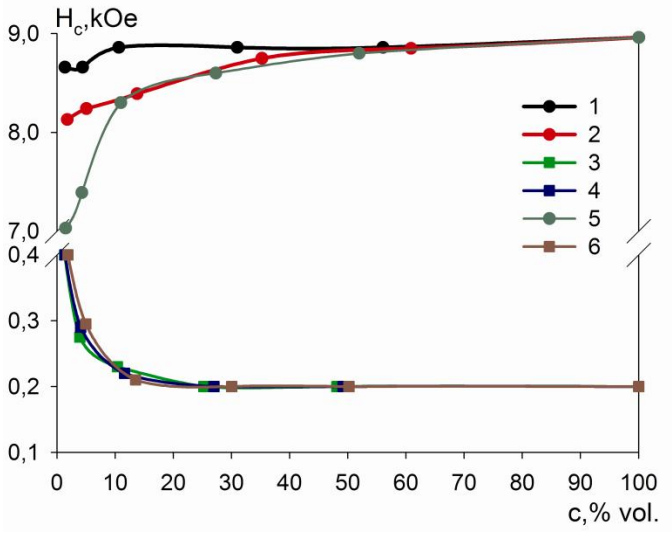


Figure 4. RMM intrinsic coercivity dependencies on the volume fraction of magnetic filler for the systems: 1-SKI-3/MQP-B, 2-PCP/MQP-B, 3-SKI-3/nano-Fe, 4-SKN-18/nano-Fe.

coercivity is almost independent on it. The type of rubber binder does not influence H_c of magnetically soft compositions. It means that surface interactions between binder and magnetic particles dispersed

in MRM based on SKI-3 and SKN-18 do not affect magnetic properties of soft MRMs. Fe nanoparticles dispersed in MRM are single-domain, having mean diameter 10-100 nm (Table 2), which is lower that critical magnetic domain size for crystalline Fe (Paine T. 1961). Magnetization reversal of these particles likely occurs due to the coherent rotation of magnetization vector M_s. Rotation of M_s to the opposite direction can happen across the activation barrier, which depends on the morphology of particles and the magneto crystalline anisotropy energy of Fe particles lattices. Thus, the value of H_c should be proportional to the anisotropy field $H_a = \alpha K/ M_s \pm \Delta n * M_s$, with α - being numerical coefficient, K – magnetic anisotropy constant of Fe provided by its crystalline structure, Δn – the demagnetization factor difference between a short and a long particle axis's if its shape differs from a sphere. As it was shown for ESD-magnets (Eisurovich A.S. 1959), the second contribution in the given equation is substantial only at relatively low filler content, when the magnetic particles are more or less independent and their own fields do not influence the neighboring particles. Due to the increase in filler content the particles get closer and their magnetic moments begin to interact. As a result Δn values for separate nanoparticles diminishes to zero. This effect is more pronounced up to 25% of filler content. Above this threshold value magnetic interactions between nanoparticles are strong and nullify magnetostatic contribution to magnetic anisotropy field and hence to H_c. Based on the spherical form of Fe nanoparticles (Figure 1) one can evaluate the mean diameter of Fe particle using the specific surface area of Fe -nanopowder (Table 2) according to the following equation:

$$< d >= \frac{6}{\rho S_{BET}}, \quad (1)$$

where S_{BET} – specific surface area, ρ - density of material. Thus, the mean diameter of Fe-nanoparticles is around 80 nm. Based on the threshold volume fraction 25% the mean interparticle distance for effective magnetostatic interaction might be estimated by 35-40 nm.

The dependence H_c=f(c) for magnetically hard MRMs filled with MQP-B lays within 8.1 – 8.9 kOe range. H_c values increase with filler content and achieve saturation both for SKI-3 and PCP composites. The influence of rubber binder on H_c reveals at low and moderate filler content. In the case of SKI-3/MQP-B intrinsic coercivity saturates at 10% of filler content, and it changes are relatively low. The intrinsic coercivity of PCP/MQP-B changes more substantially, almost linearly, and saturates at cρ=50%.

The possible explanation of these features might be as follows. Although the particles of MQP-B are strongly irregular in shape, their crystal structure is isotropic, because it consists of chaotically oriented grains of magnetically uniaxial highly anisotropic $Nd_2Fe_{14}B$ phase with mean grain size 20 nm and nano-grains of α-Fe with approximately the same size in exchange interaction (Kudrevatykh N.V. et al. 2011). Each polycrystalline microparticle is adhesively bound to polymeric matrix, which can provide mechanical stress upon magnetic particle in form of elongation or contraction. The magnetostriction of rare-earth alloys is substantially higher than for Fe (Andreev A.V. et al. 1986), therefore these mechanical stresses originating from polymeric matrix can substantially contribute to the magnetic anisotropy of nano-grains of $Nd_2Fe_{14}B$ and influence exchange interactions between grains as well. We think that it is the underlying reason for the decrease of H_c of hard MRMs at low filler content. If the volume fraction of magnetic filler is increased, the polymer content in composition decreases so does the mechanical stress that polymeric matrix applies upon magnetic particles lower. As a result H_c values saturates at the level, which is close to that for the individual MQP-B powder. If interfacial interaction between magnetic particle and polymer matrix is strong, like in the case of polar PCP (Petrov A.V. et al. 2010), the mechanical energy stored in polymer matrix is high, therefore its influence on H_c is stronger and remains up to higher filler content.

Interactions between magnetic fillers and rubber binders affect the mechanical properties of MRMs, which are the major concern in practical application of these composites. The values of breaking strain, Young's modulus at 20% elongation, and stress-at-break for all MRMs under study are presented in Table 3. For all composites the increase in filler content results in consequent increase in Young's modulus and the decrease in breaking strain. The comparison of mechanical properties between composites with different type of binder but the same filler content reveals that the increase in the polarity of binder results in the decrease of ε and the decrease of E at any filler content.

Table 3. Mechanical properties of MRM

Filler content % wt	SKI-3/MQP-B			PCP/MQP-B			SKI-3/nano-Fe			SKN-18/nano-Fe		
	ε,%	E, MPa	σ_p, MPa	ε,%	E, MPa	σ_p, MPa	ε,%	E, MPa	σ_p, MPa	ε,%	E, MPa	σ_p, MPa
10	1070	0,76	1,9	630	1,95	9,9	950	0,73	4,5	420	2,16	1,9
25	960	0,88	2,1	545	2,32	8,4	865	0,91	6,1	440	2,35	2,2
50	910	1,04	1,7	460	2,94	5,8	770	1,45	10,2	390	4,06	3,9
75	860	1,40	1,9	440	5,48	3,6	530	2,84	9,8	150	10,2	5,3
90	530	2,90	1,3	60	8,95	1,7	120	10,5	2,3	12	42,7	5,4

Although the trend of the increase of E with filler content is the same for all composites, the specific features for different MRM could be readily notices from Table 3. In general, mechanical properties of composite depend in very complicated and integral way on type of polymer matrix and the filler, structural properties of composite and the interfacial energy between matrix and immersed particles. Young's modulus of MRM filled with nano-Fe at high loading is substantially higher than that of MRMs filled with MQP-B. The possible explanation is the different morphology of particles for these two fillers. It is clear from Figure 1 that MQP-B particles have irregular shape, which is very unfavorable for the uniformity of applied mechanical stress distribution in polymeric matrix. The nano-Fe particles have regular spherical shape that provide more uniform distribution of mechanical stress, which effectively leads to the higher values of Young's modulus of composition.

Even stronger influence of the irregular morphology of MQP-B particles might be clearly traced out considering the stress-at-break values for composites. MQP-B particles have multiple sharp edges (Figure 1), which are fatal for the continuity of polymeric matrix under the applied stress. Therefore, the stress-at-break diminishes with the increase of MQP-B filler content in MRM. On the contrary, the increase of filler loading in the case of nano-Fe results in the strengthening of MRM and higher values of σ_p. If the filler improves the mechanical properties of filled composite it is considered as "active", in the opposite case it is defined as "inactive" (Gul' V.E. 1966, Lipatov Yu.S. 1967). From this conventional point of view nano-Fe powder should be classified as an active filler, while MQP-B as an inactive one.

3.2.A study of specific attraction force (F) between steel and MRM sheets

As it was already mentioned, the desirable shape of MRM for technology purposes might be the thin elastic sheet with strong attractive force (F) to ferromagnetic bodies and surfaces. This force mostly depends on the magnetic energy stored by MRM upon its magnetizing, which is proportional to the maximum energy product of the filler $(BH)_{max}$, filler content, sheet thickness and "magnetic picture" on its surface – namely the area, shape and positions of magnetic poles created on the MRM sheet during its magnetizing by special inductor. Magnetic picture should be determined by the desired properties of MRM sheet, which stem from the specific objectives of its application.

These may for example include a requirement of maximum possible specific attraction force (F) of HMR to the surface of ferromagnetic material at the fixed thickness MRM (if using MRM as seals or special coatings to surfaces of details made of ferromagnetic materials) or requirement of maximum extension of magnetic field generated by MRM magnetic poles (in case of their use as applicators or magnetizers of surrounding environment). In this regard, it is obvious that the number of magnetic poles on the surface of the sheet and the geometrical pattern of magnetic poles, as well as the internal magnetic structure of magnetic domain (a volume with the same average orientation of residual magnetization of filler particles) should depend on the specific assignment of MRM. The studies on attractive force F value depending on the geometrical and magnetic characteristics of MRM are presented below.

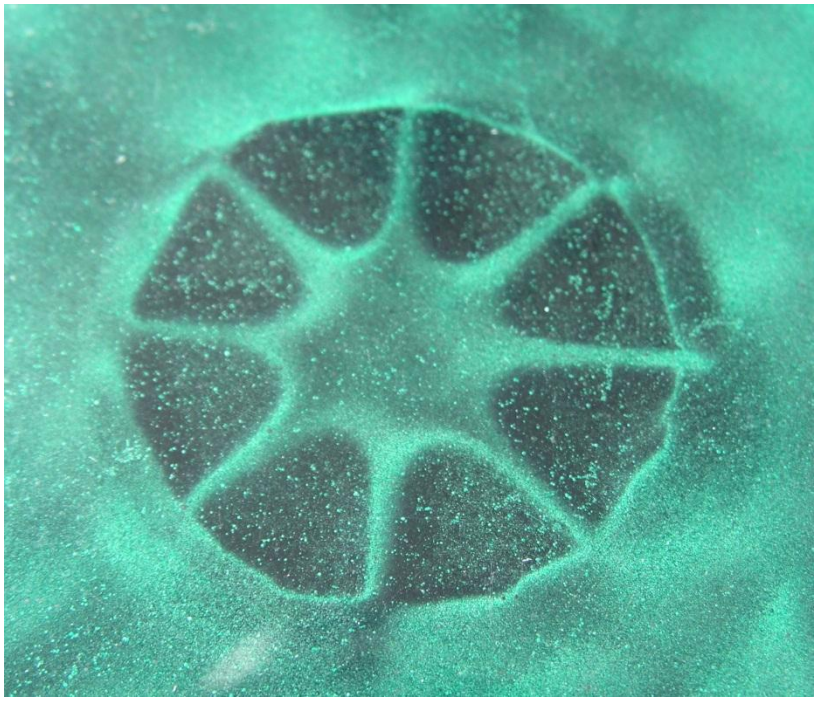


Figure 5. – Magnetic poles patterns picture on the surface of MRM disk D=28 mm, named as – "eight-petal rose" (8r) after its magnetizing by special electric current inductor. Patterns have been visualized with a help of an indicator magnetic film.

Experimentally, the dependences of magnetic-force parameter – specific attraction force (F) of MRM to the surface of a 10 mm thick steel sheet have been studied on:

a) the concentration (**c**) of a magnetic hard powder filler - F(**c**) (**c**=70; 80; 90 % wt.), at constant: disk thickness (H) =2,0 mm; magnetic poles pattern –"eight-petal rose" (8r); (Fig. 5); total "back' magnetic poles closing with the help of silicon-iron plates (d= ∞);

b) the hard magnetic rubber (HMR) disk thickness (H) – F(H), (H= 1.0÷3.0 mm) at constant: concentration (**c**) of a magnetic hard powder filler (c=90%); magnetic poles pattern –"eight-petal rose" (8r); total "back' magnetic poles closing with the help of silicon-iron plates (d= ∞);

c) Magnetic poles number (n) at the HMR disk surface – F(n) having the "Kittel" like magnetic poles picture (parallel to diameter "magnetic strips" of the same widths) (n=1 ÷ 6) at constant: concentration (**c**) of a magnetic hard powder filler (**c**=90%); disk thickness (H=1.7 мм); total "back' magnetic poles closing with a help of silicon-iron plates (d= ∞);

d) the thickness (d) of a soft magnetic rubber (SMR) layer closing the "back" magnetic poles with a 85% soft magnetic powder (nano-Fe) filler concentration - F(d) (d= 1.0 ÷3.5 мм) at constant: concentration (**c**) of a magnetic hard powder filler (**c**=90%); magnetic poles pattern –"eight-petal rose" (8r); disk thicknesses H = 1.2, 1.6. 2.2. 2.6 мм;

e) the air gap size (h) between HMR and a 10 mm steel thickness sheet surfaces – F(h) (h=0 ÷1.0 мм) at constant: concentration (**c**) of a magnetic hard powder filler (**c**=90%); disk thickness (H=1.7 mm); magnetic poles pattern –"eight-petal rose" (8r); "back' magnetic poles closing with a help of silicon-iron plates (d= ∞) and SMR band on the α-Fe filler base (**c**=85%) with d= 1.7, 2.2 mm.

On the basis of the study, the combinations of **c**, H, d, n, h have been empirically found, which provide F ≥ 200 g/cm^2. Their values are listed in Table 4. The study clearly shows that the higher values of attraction

Table 4. The values of a disk shape MRM parameters having the specific attraction force to the steel plate surface equal to 0,2 кг/см^2 or more.

C (%)	H (mm)	d (mm)	n	h(mm)
70	Not realized			0,0
80	Not realized			
90	1,2	∞	8r	0,0
	2.5	0	8r	0,0
	1.2	2.6	8r	0,0
	2.2	1.2	8r	0,0
	1.7	∞	2	0,0
	2.2	1.7	4	0,0
	1.7	∞	6	0,0
	1.7	1.7	8	0.15
	2.2	∞	4	0.50

force F are attained at a multipolar magnetic pole patterns on the surface of the MRM disk. In this connection, the question of the optimum number of magnetic poles, giving the maximum values for F arises. The answer we were searching both theoretically and experimentally. Theoretical calculation was performed with a special computer program (Program Package Comsol Multiphysics) under the following conditions: HMR sheet thickness - 2.0 mm, concentration filler **c**= 90%, sheet width W = 28 mm, length = ∞, magnetic poles picture – "Kittel" like, the back poles are not closed. The theoretical dependence F=f (h) on the air gap between HMR and steel sheet is shown in Figure 6 for the samples with different number of magnetic strips (n). As it is seen when the strips number (n) increases (at the fixed MRM sheet) the F(0) value sharply grows. However when the air gap between MRM sheet and the steel plate surface appears (h≠0) the F(h) value diminishes on h much steeper for MRM samples with higher n. This relationship was confirmed by the experiment when magnetized bipolar HMR disk was cut into strips with different width, which then were rearranged to form alternating poles sequence (Figure 7).

Thus, computations and experiments show that for each particular geometry of magnetic poles pattern on the surface of magnetic rubber sheet there is an optimal value of n, when the specific attraction force is reasonably high not only at zero gap but at some distance as well. This can serve as a guarantee for reliable magnetic rubber sheets "adhesion" not only to the flat steel surfaces but also to waved ones and those having corrosion places. However, it should be noted that a large number of magnetic poles on a limited HMR area might not be achievable due to the impossibility of constracting an adequate magnetizing device (inductor).

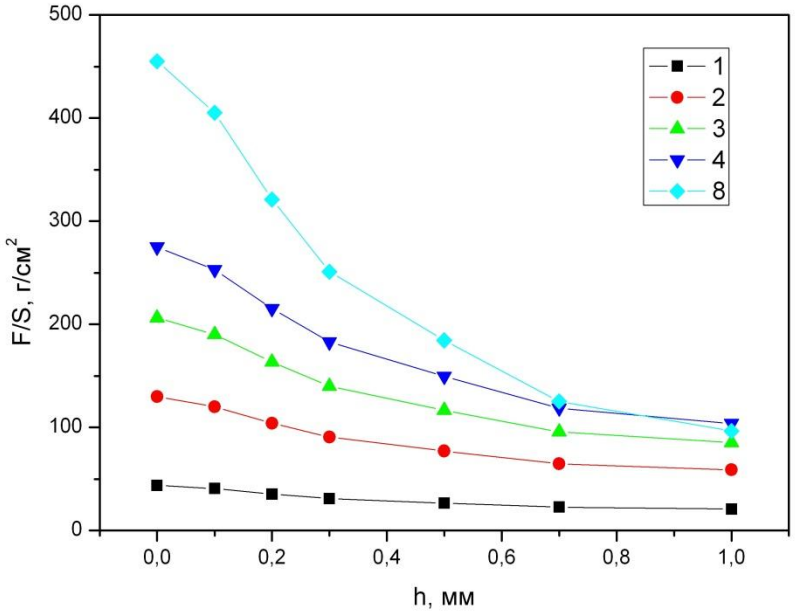


Figure 6. The calculated dependences of specific attraction force of HMR sheet to the steel plate surface on the air gap width (h), having a different number of magnetic poles (strips) (n) at the fixed sheet area surface. Poles (strips) number is pointed in insertion frame.

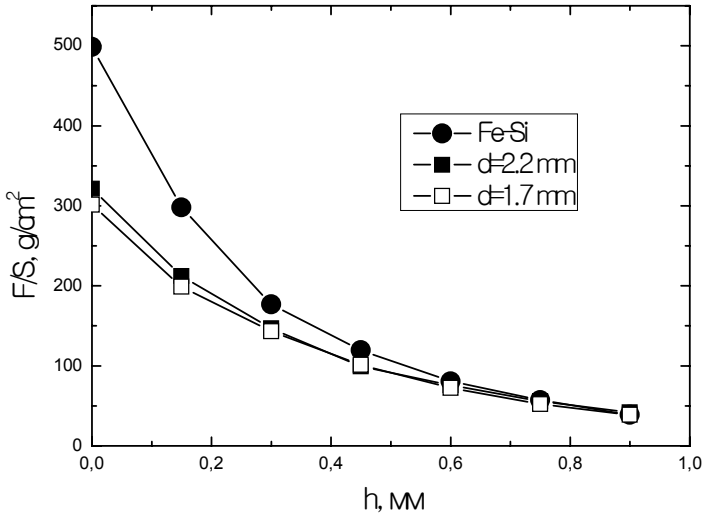


Figure 7. Experimentally determined specific attraction force value of HMR disk with 28 mm diameter to the 10 mm thickness steel plate on the gap size width between them at different thickness of back poles closing SMR layer. Magnetic poles disk pattern is "eight-petal rose" (8r); back poles are closed by three different soft magnetic material plates: ■, □ – made from SMR (**c**=85%) with thickness respectively 2.2 and 1.7 mm; ● – from Fe-Si plate of 2,0 mm thickness.

3.3. Magnetic inductors for HMR magnetizing with multi poles patterns

Multipolar magnetizing of HMR sheets in the pattern of alternating magnetic pole strips – "Kittel" like structure (the easiest one to implement magnetizing option) or more complex patterns - "eight-petal rose", "chess board" is a non-trivial technical challenge. It requires a special geometry of the magnetic inductors capable to carry a high-power electric current through them, generating large magnetic fields capable to magnetize a magnetic filler up to the full magnetic saturation (inside of magnetic domain). In addition, the inductor must cover by poles as much HMR surface area as it possible, i.e. to provide the minimal width of the transitional zones from one pole polarity to the other. The inductor, which is a flat lattice of parallel conductors of electric current with alternating direction meets this requirement the best. A scheme of this inductor is shown in Figure 8.

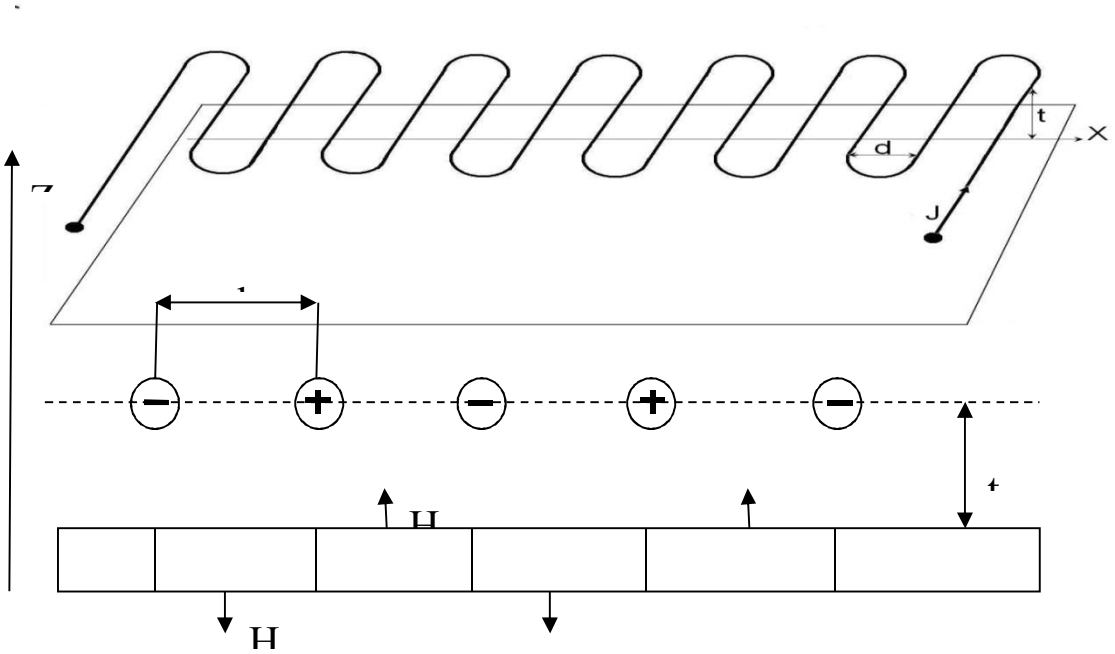


Figure 8. Diagram of a simplest inductor for multipolar HMR sheet magnetizing. Inductor represents a flat lattice of parallel conductors having an electric current from alternating directions it goes.

The desired maximum value of the magnetic field generated by inductor is determined by the magnetic characteristics of the filler. In the case of Nd-Fe-Co-B alloy filler, its value must be 20 kOe (1600 kA/m) and above. It can be seen from Figure 9, where the values of intrinsic coercivity (H_c) and specific residual

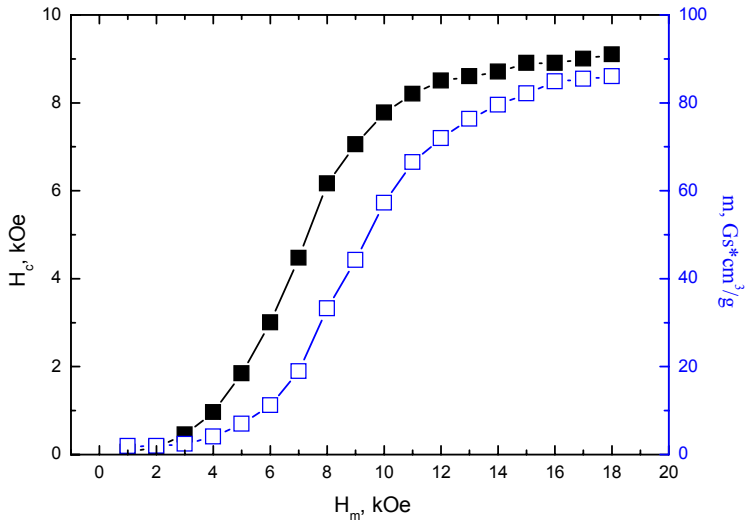


Figure 9. Experimentally determined values of intrinsic coercivity -H_c (■) and specific residual magnetization -m_r (□) dependencies for Nd-Fe-Co-B type (MQP-B) nanostructured alloy filler as a function of external magnetizing field (H_m).

magnetization (m_r) as a function of magnetizing field (H_m) are presented. Such magnetic field intensity can be created at least using a iron-core electromagnet. However, in case of a core free wire coils, such field generation requires a very large electric currents. We have calculated the values of normal magnetic field component (H_z) produced by inductor shown in Figure 8, as a function of an x-coordinate at different distances t between the inductor and magnetized HMR sheet with a 0.5 mm step. A semi period d in conductor lattice made of the 2.7 mm diameter wire was varied from 5 up to 20 mm. The value of electric current power was taken as 1000 amperes. A typical magnetic field $H_z(x)$ topology picture for the d=10 mm is shown in Figure 10.

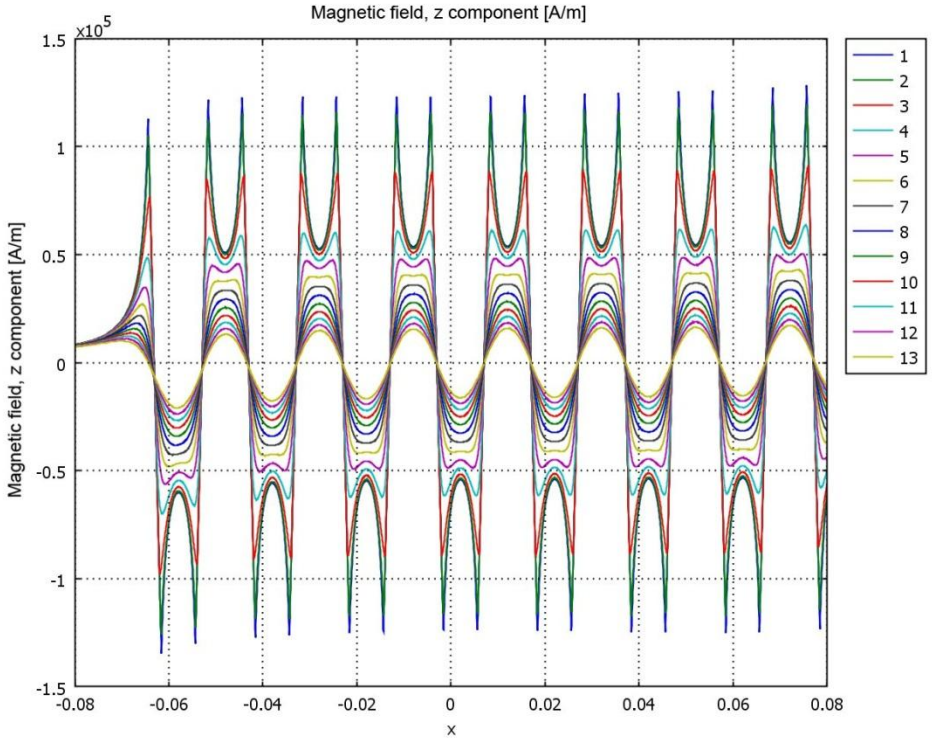


Figure 10. Calculated magnetic field $H_z(x)$ topology picture produced by shown in Fig. 8 inductor for d=10 mm and 1000 A passing electric current at different distances (t) between an inductor and MRM planes:

1 – t=0.0 mm; 2- t= 0,5 mm; 3- t=1,0 mm; 4 - t=1,5 mm; 5- t=2,0 mm; 6- t=2,5 mm; 7 - t=3,0 mm; 8- t=3,5 mm; 9 – t=4,0 mm; 10 – t=4,5 mm; 11- t=5,0 mm; 12 – t=5,5 mm; 13 – t=6,0 mm.

In general, these calculations have shown that there is an optimal distance between conductors, when the inductor is capable to create the desired magnetic field intensity for HMR magnetizing throughout its total depth (thickness). But the H_z-field component at a current intensity of 1000 A was too low for full magnetizing of 2 mm HMR sheet filled with MQP-B powder. Such inductor needs to be feed by the electric current of 30 times lager. In practice, a single unipolar electric current pulse from a special power supply is used. The best of them is electric capacitors battery about 10 -50 mF which are charged up to several thousand volts (Nesterin V.A. 1995). The disadvantage of this technique is the necessity to cool the inductor, which is overheated during frequent pulses of a strong current. In addition, a large current creates the so-called ponderomotoric forces that can destroy or make shorting

of inductor wires. In this regard, the construction of such inductors has to be enhanced by special bandages that further complicate the manufacturing and increase the cost. It should also be noted that the weak point of this method of multipolar magnetizing is its low productivity because a current pulse "prints" magnetic poles picture on a relatively small MRM sheet surface area. Alternative is the magnetic system composed of the permanent magnets. This option is economically preferable because it omits inductor manufacturing, an electric energy power supply, a charger and discharger devices, and of course, an additional electric power consumption from the AC power net.

We have made the calculation of such permanent magnetic system shown in Figure 11 using the above mentioned computer program. Its basic element is a high-energy Nd-Fe-B type permanent magnets with $(BH)_{max} > 40$ MGsOe. Their volume is determined by the size of the gap (the width and height), as well as the required intensity of the magnetic field in the gap. The following parameters were set: width of pole tip w = 8 mm, spacing between the poles (d) = 2.5 mm, the magnetic field intensity in the gap -at least 25 kOe. Of course, this system would be able to magnetize large HMR sheet when it is pulled out through the gap making only one "magnetic" stripe with a width of about 8-9 mm. For multipolar magnetizing it will require repeated entries of HMR sheet to the gap space with its 180 degrees rotation around the horizontal axis and

sideward shift at the pole tip width. Visualized calculation results are presented in Fig. 12. According to

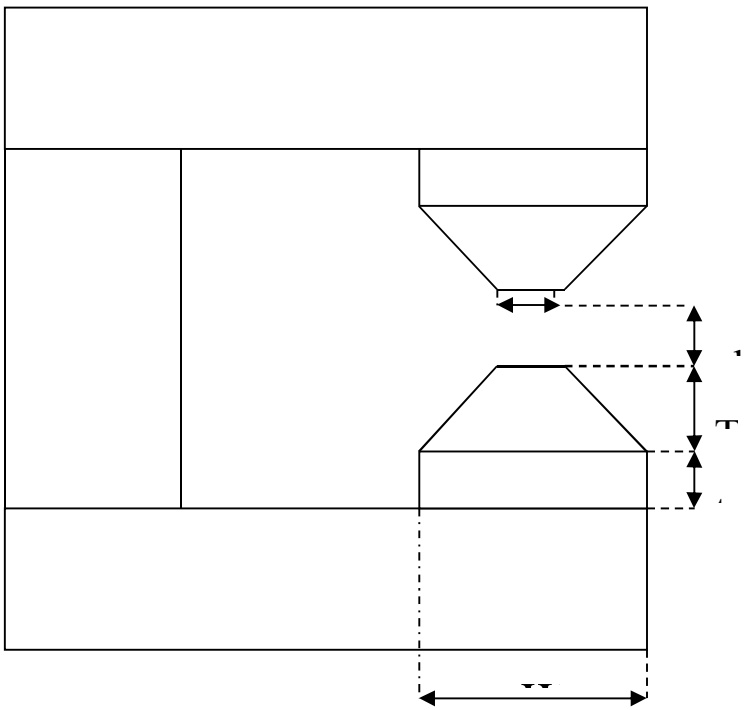


Figure 11. Magnetic circuit configuration from the permanent magnets, pole pieces and iron york used in computer calculation: t-thickness of a permanent magnet; W-width of a rectangular permanent magnet, T is the height of a conical pole tip; t – base pole height; d- spacing between the poles; w- tip width. Adjacent to the magnets rectangles made from soft magnetic material form a york.

these data the establishment of such system is possible using 8 pieces of Nd-Fe-B type permanent magnets of 30 x 25 x 10 mm in size. The manufactured system with such geometry design is presented in Fig. 13. The magnetic field intensity in the gap was 20 ± 1 kOe that fits well the calculated value. Thus both by computer simulation and experimentally we have shown that HMR sheets filler with hard magnetic Nd-Fe-Co-B powder can be magnetized practically up to saturation without an electric current inductor (with much lower operating costs) but by pulling them through the gap space of a specially designed magnetic system. This way we performed multipolar magnetizing of 110 x 110 x 2 mm HMR sheet. Being placed between two steel tiles this HMR sheet can attract them with the force not less than 20 kg (fig. 14).

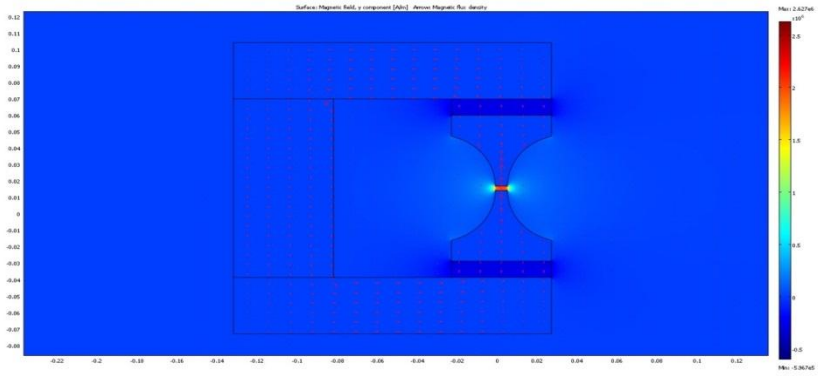


Figure 12. The distribution of magnetic field z-component (in color) around the permanent magnets system shown schematically in Fig. 11 plotted on the base of computer calculations.



Figure 13. The photo of created magnetic system with permanent magnets for a “Kittel” like magnetic poles picture formation on the surface MRM sheets. The magnetic field intensity in cavity is 20 ± 1 kOe.



Figure 14. Demonstration of the "work" of magnetized rubber. Placing it between two steel tiles it gives them the attraction force of not less than 20 kg.

4.CONCLUSIONS

The main results of the study are:

1. The development of methods of synthesis and samples manufacturing of "magnetic rubber materials" (MRM) based of synthetic rubbers filled with the powders of hard and soft magnetic materials (respectively hard magnetic rubber - HMR and soft magnetic rubber –SMR).

2. The determination of MRM residual magnetization and intrinsic coercivity dependence on the volume content of hard and soft magnetic powder fillers with different types of polymer resins.

3. The determination of mechanical characteristics of MRM and confirmation that the typical elastic rubber properties remain.

4. The calculation and experimental verification of a specific attraction force (F) between MRM and steel sheets on: a) filler concentration; b) HMR thickness; c) magnetic poles density (number); d) soft magnetic rubber thickness closing the back magnetic poles on HMR surface; e) air gap width between HMR and steel sheet surfaces. Preparation of MRM bilayered samples with F= 0.3-0.4 kg/cm^2 at their thickness 1.5-2.0 mm.

5. Design and manufacturing of magnetic system on the basis of high magnetic energy product Nd-Fe-B type permanent magnets, which allow producing multipolar MRM sheets magnetizing to extremely high values of residual magnetization in magnetic "stripes".

6. Manufacturing of 110 x 110 x 2 mm MRM sample based on polymeric SKN-18 binder filled with MQP-B brand powder with attraction force to the surface of the steel plates of similar area not less than 0.2 kg/cm^2 (total attraction force more than 20 kg).

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Program Package Comsol Multiphysics: http://www.comsol.com/