ISSN 0027-1349, Moscow University Physics Bulletin, 2017, Vol. 72, No. 1, pp. 80–87. © Allerton Press, Inc., 2017.
Original Russian Text © E.V. Milov, I.A. Sipin, V.N. Milov, A.S. Andreenko, I.A. Balan, 2017, published in Vestnik Moskovskogo Universiteta, Seriya 3: Fizika, Astronomiya, 2017, No. 1, pp. 78–85.

CONDENSED MATTER PHYSICS

Investigation of Energy Losses in Low-Coercivity Resin-Bonded Magnets in Alternating Magnetic Fields

E. V. Milov, I. A. Sipin, V. N. Milov, A. S. Andreenko*, and I. A. Balan

Faculty of Physics, Moscow State University, Moscow, 119991 Russia

**e-mail: asa@phys.msu.ru*

Received August 8, 2016; in final form, October 24, 2016

Abstract—Energy losses during alternating remagnetization of low-coercitivity resin-bonded magnets and commercially produced electrical steels were studied experimentally. The studies were conducted on several samples of resin-bonded magnets with different manufacturing technologies and samples of electrical steel sheets of various thicknesses. The static and dynamic magnetic properties of the samples were measured on a vibration magnetometer and a specially designed apparatus, respectively. It was found that the studied samples of bonded magnets have a relatively high level of hysteresis losses associated with high coercivity, which reaches a value of 4–5 Oe. At the same time, the remagnetization losses due to the Foucault currents in the bonded magnets are considerably lower than in electrical steels. The measurement results show that bonded magnets at high frequencies of remagnetization, especially in high-rpm motors, can be competitive in comparison with electrical steels.

Keywords: bonded magnets, magnetic reversal frequency, magnetization, energy losses, Foucault currents, coercitivity, hysteresis losses.

DOI: 10.3103/S0027134917010118

INTRODUCTION

Development of energy-efficient devices that save the energy resources of the planet is one of the main tasks of modern technology. In particular, electric machines (EMs) for various purposes with a wide range of output powers and with a high coefficient of performance (COP) are of key importance. Achievement of high efficiency requires finding solutions to several design problems and development of new technologies for manufacturing electric machinery.

One way to increase efficiency is to reduce energy losses in periodic remagnetization of work elements of electrical machines (rotors or stators). There are three main factors that determine the major losses during the operation of EMs: mechanical losses, loss due to the windings of stators and rotors, and losses directly in magnetic materials used in manufacturing EMs. The first two sources are mainly due to the design of EMs, while the losses in magnetic materials are due to their magnetic and electrical properties. In this work, the first two sources of losses in EMs are not considered.

The quantitative relationship between the loss sources significantly depends on the power of an EM; according to expert estimates [1, 2], the losses directly in magnetic materials are in the range of 29–59% of the total loss value. The energy losses in electrical steel, which, as a rule, is used for making stators and rotors, include the losses due to hysteresis and due to the occurrence of additional currents (Foucault currents) upon periodic remagnetization.

Usually reduction of the losses is achieved by using thin sheets of electrical steel in the EM manufacturing process with excellent magnetic properties as a material for the cores of rotors and stators. However, an alternative material for the cores is bonded magnets on the basis of magnetic iron powders, for which one can a priori expect an increase of the electrical resistance and therefore a decrease of the Foucault currents with a slight deterioration in magnetic properties. This work is aimed at studies of the magnetic and electrical properties of bonded magnets in comparison with similar properties of electrical steels.

1. EXPERIMENTAL TECHNIQUES AND SAMPLES

The magnetic properties of soft magnetic materials were measured using a vibrational magnetometer to allow magnetization measurements in magnetic fields up to 21 kOe at room temperature. The scheme and description of the magnetometer were given in [3].

Without elaborating the work parameters of the magnetometer, we note that for measurements of soft magnetic materials and accurate determination of the coercive force in these materials the magnetometer

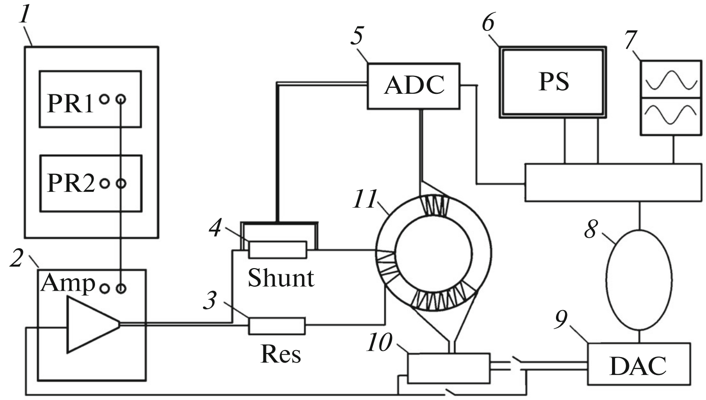

Fig. 1. A block diagram of the experimental apparatus: *1*, two connected in parallel Mastech HY3040Y power supplies, U_{max} = 30 V, J_{max} = 40 A; *2*, PH2500M amplifier, U_{max} = 55 V, J_{max} = 30 A; *3*, load resistance, R_{load} = 1.25 Ω; *4*, shunt, R_{shunt} = 0.1 Ω; *5*, 2-channel 16 bit ADC with a frequency of 2.5 MHz; *6*, IBM PC Intel Pentium 4 3.00 GHz; *7*, transformer for network isolation; *8*, galvanic isolator, connected by a USB interface; *9*, PCM2704 16 bit DAC; *10*, feedback unit; *11*, studied sample.

was operated in the mode of non-linear field change. The time dependence of the field strength consisted of fragments of the cos(x) function, which were combined in the (0–π/2) phase interval in such a way that as the field approaches zero its time derivative also tends to zero. In other words, for the accurate measurement of small values of the coercive force in critical areas, the speed of magnetic-field scanning is reduced without loss of the monotonicity of the magnetic field change.

To study the remagnetization processes and measurement of magnetic losses in soft magnetic materials we designed and constructed an experimental apparatus that allows us to measure these characteristics in a closed magnetic circuit made of the studied material. A block diagram of the apparatus is shown in Fig. 1.

The apparatus was designed to perform measurements for materials with low magnetic permeabilities. As a consequence, a high level of magnetic field intensity was necessary. This was done using a PH2500M linear audio amplifier of low frequency (2) which underwent considerable modification, including changes in the filter and the feedback circuits, which allowed one to increase the gain and widen the frequency range up to 30 kHz. The modification involved the replacement of complementary pairs of transistors at the amplifier output with 2SC5200 (*n*–*p*–*n*) and 2SA1943 (*p*–*n*–*p*) transistors. A total of four complementary pairs in parallel connection are used at the output. Thus, considering that the nameplate power dissipation of each transistor is 150 W, the maximum power dissipation of the amplifier was 600 W at a constant output current and 1200 W under AC. The amplifier was powered by two Mastech HY3040E power supplies connected in parallel which allowed us to obtain a maximum current of 30 A and a voltage of 55 V at the amplifier output.

The signal at the amplifier input came from a 16 bit PCM2704 DAC (9), which was connected via USB through a galvanic isolator (8). The computer control of the signal allowed us to implement a procedure for preliminary demagnetization of the sample, as well as to apply a signal of a specified duration, amplitude, and frequency. This makes it possible to perform measurements at high currents, which are not achievable in the stationary mode due to overheating of the sample or amplifier.

The amplifier is connected to the tested sample (11) through a load resistor with a power of 1.5 kW and a shunt current (1% 0.1 Ω). The sample is a toroid on which three coils are wound, including a coil (100–200 turns) which creates magnetic field H, a measuring coil (5–12 turns), and a feedback coil (2–5 turns).

The measuring coil and current shunt are connected to a 2-channel 16 bit ADC (5) with a frequency of 2.5 MHz. This device is a PCI card (manufactured by the Instrumentalnie sistemi LLC) that is connected to an IMB PC. This approach allows the performance of all of the procedures of signal processing in the digital form. Due to the nonlinear dependence $B(H)$ in the measured materials, the time dependence of the induction, the EMF of the induction, and the field strength become nonsinusoidal, even when the time dependence of the voltage at the generator output is strictly sinusoidal. The presence of higher harmonics in the EMF signal increases the power loss in the material due to the conduction currents, so the measurement of magnetic losses should be conducted under strictly sinusoidal time dependence of the induced EMF. The measurements of the losses at a certain frequency are enabled only in this case. In order to measure the sinusoidal time dependence of the induction, the experimental apparatus contains a specially designed negative feedback unit, which makes it possible to control the magnitude of the induction in the sample. The signal that the unit transmits to the DAC is proportional to the time derivative determined by the time dependence of the induction.

To run the experimental apparatus, we developed a code to allow automatic measurements of the amplitude-frequency characteristics of a sample.

The resistivity of the toroidal samples was determined by the four-contact method. The current contacts were connected to the diametrically opposite points of the ring, whereas the voltage drop was measured at two 4-centimeter segments of chords using an Agilent 34420A nanovoltmeter. The results of two measurements on chords were averaged. The magnitude of the current was varied from 20 mA to 0.1 A and controlled by a Keithley 2000 multimeter.

Samples of extruded metalloplasts for measurements on the vibrating magnetometer were cut using the electro-erosion technique. To reduce the influence of the demagnetization factor, the samples had the shape of an elongated rectangular parallelepiped. Samples of bulk density were prepared of loose powder that was not subjected to pressing. Particles of metal powder were glued together with epoxy resin (ER) in the form of discs 3 mm in diameter and 1 mm in height. For powders with large particles, there was an opportunity to study individual particles.

The samples for measurements in the closed magnetic circuit were prepared by extrusion using a hydraulic press equipped with hard-alloy tooling. The extrusion pressure can be controlled and set in the range from 1 to 10^4 kg/cm^2. Table 1 shows the prepared samples of 2 types of iron powder Fe no. 1 and Fe no. 2. Both the powders were obtained by the gas-atomization method of pure iron. The average particle size of both powders was 100 μm, while the maximum particle size was 200 μm. The particles of the second powder after production were covered by a polymer layer

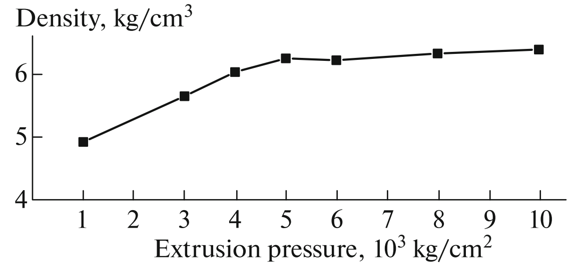

Fig. 2. The dependence of the density of bonded magnet material on the extrusion pressure.

in weak solutions of polyester resins. The weight percentage of these resins in the resulting isolated powder did not exceed 0.2%. In addition, a commercially available powder of Fe + 6.5% Si + 4.5% Cr with an average particle size of 142 μm was used to prepare samples. To improve the mechanical characteristics, the powders were mixed with a polyester binder with a weight content of from 0 to 3%. After pressing, all of the samples were subjected to heat treatment at 200°C.

All the samples had the form of toroidal rings with the same outer and inner diameter, but the height had a scatter of approximately 20%, which was taken into account in the measurements; the average height was 5 mm.

2. EXPERIMENTAL RESULTS

2.1 Measurements of the Density of Bonded Magnets and Their Electrical Resistance

The magnetic and electrical properties of bonded magnets depends on their manufacturing techniques, in particular the number of polymer ligaments and extrusion pressure. Figure 2 shows the dependence of the density of the iron powder no. 1 (Table 1) on the

Table 1. Studied samples

Magnetically soft powder	Amount of polymer binder, %	Extrusion pressure, 10^3 kg/cm^2	Number of samples	Inner diameter, mm	Outer diameter, mm
Fe no. 1	1.5	8	2		
		1	2		
		3	2		
		4	2		
	2	5	2		
		6	2		
		8	4	36.9	40.9
		10	2		
	2.5		3		
	3 + (10% TiO_2)		2		
Fe no. 2	0	8	2		
	2		2		
Fe + (6.5% Si) + (4.5% Cr)	2		2		

Table 2. The composition, density, and specific resistivity of studied samples of bonded magnets

No.	Brand	Extrusion pressure, 10^3 kg/cm^2	Sample	Mass, g	Density g/cm^3	R_{sp}, Ω cm
1	Fe no. 1 1.5% ER	8	1.1	7.61	6.34	0.74
			1.2	7.89	6.34	0.71
2	Fe no. 1 2% ER	1	2.4.1	6.04	4.91	–
			2.4.2	5.72	4.93	–
		3	2.5.1	6.63	5.66	–
			2.5.2	6.88	5.65	–
		4	2.6.1	6.98	6.02	–
			2.6.2	7.05	6.05	–
		5	2.7.1	7.26	6.26	–
			2.7.2	7.32	6.25	–
		6	2.1.1	8.02	6.26	1.94
			2.1.2	7.93	6.19	1.57
		8	2.2.1	7.88	6.33	2.04
			2.2.2	6.39	6.32	1.22
			2.2.3	7.20	6.28	2.20
			2.2.4	8.04	6.40	2.88
		10	2.3.1	8.04	6.34	0.71
			2.3.2	8.19	6.46	1.51
3	Fe no. 1 2.5% ER	8	3.1	7.49	6.27	2.22
			3.2	7.88	6.57	2.04
			3.3	7.41	5.84	2.44
4	Fe no. 1 3% varnish 10% TiO_2	8	4.1	6.06	5.21	22.21
			4.2	8.17	5.27	3.77
5	FeSiCr 2% ER	8	5.1	6.47	5.41	26.62
			5.2	6.55	5.44	40.13
6	Fe no.2 2%ER	8	6.1	8.31	6.43	1058.00
			6.2	7.97	6.34	1762.20
7	Fe no.2	8	7.1	8.01	7.06	6.67
			7.2	8.31	7.02	38.33

extrusion pressure when the mass concentration of the polymer binder is 2%. As seen, the density increases linearly when the pressure is in the range from 0 to 5 × 10^3 kg/cm^2, while it is practically a constant in the range from 5 to 10^4 kg/cm^2.

At the same time, the experiment showed that the amount of the polymer binder practically does not affect the density when the extrusion pressure is 8 × 10^3 kg/cm^2.

As can be seen from Table 2, the electrical resistivity of the iron no. 1 sample, which consisted of particles that were not covered with the insulating layer, also exhibits no dependence on the extrusion pressure in the range from 5 to 10^4 kg/cm^2, except for a significant drop at the maximum pressure of 10^4 kg/cm^2.

For iron powder no. 2, whose particles were initially covered with an insulating coating, the sample that was extruded without the binder had a resistance 2–3 times greater than the best samples of iron powder no. 1 with 2% binder. As the amount of binder increased to 2%, the resistance of samples made from iron powder no. 2 grew by more than 2 orders of magnitude.

The highest resistance was observed for sample no. 6.2: 1762 Ω cm at a density of 6.34 g/cm^3.

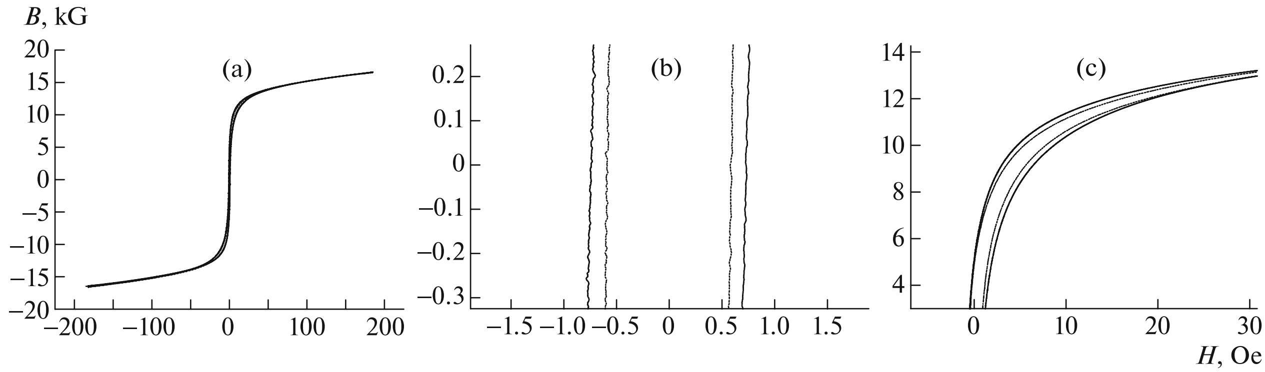

Fig. 3. (a) Hysteresis loops for the samples of grade 2412 and 2421 steels (b, c) part of the hysteresis loops near the zero magnetic field and accurate determination of the coercive force. Solid line, grade 2421 steel, thickness 0.18 mm; dashed line, grade 2412 steel, thickness 0.35 mm.

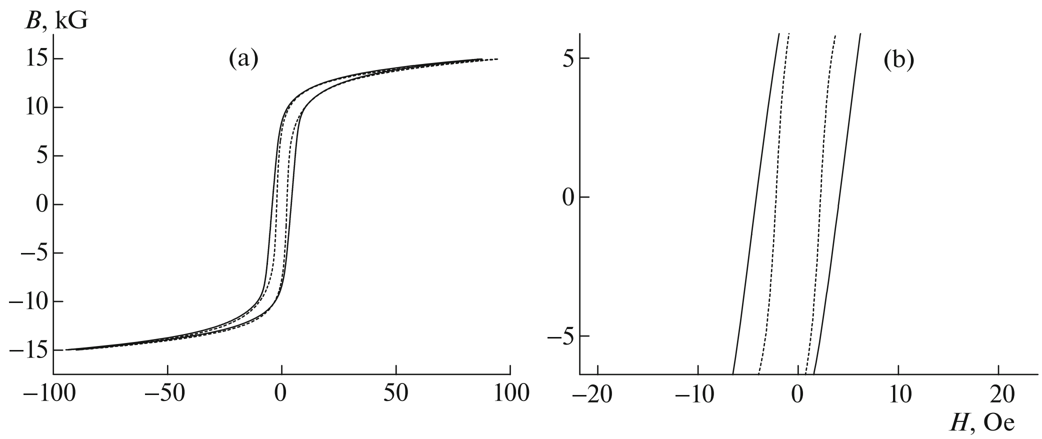

Fig. 4. Hysteresis loops of (solid line) grade 2412 steel and (dotted line) grade 2421 steel measured at a frequency of 800 Hz.

2.2 Magnetic Losses in Electrical Sheet Steels

For comparative analysis of magnetic losses in magnetically soft bonded magnets and in industrial electrical steels, we measured magnetic losses in two samples of electrical steels: grade 2412 (sheet thickness of 0.35 mm, GOST (State Standard) 21427.2-83, manufactured by NLMC, Lipetsk) and grade 2421 (sheet thickness of 0.18 mm, manufactured by AshinskyMetallurgical Works).

Figure 3 shows hysteresis loops of these two electrical steel grades measured at a frequency of 10 Hz. As is seen, the hysteresis loop of the 0.35 mm thick sample is inside the hysteresis loop of the 0.18-mm thick sample. Respectively, the remagnetization losses for the 0.35-mm thick steel is substantially less than for the 0.18-mm-thick sample. It should be noted that hysteresis loops measured at a frequency of 10 Hz can be considered quasi-static, since the hysteresis losses at this frequency are much higher than induction losses. The coercive forces determined from the hysteresis loops are close to the values given in GOST (State Standard).

Figure 4 presents the hysteresis loops for the same samples, measured at a frequency of 800 Hz. In this case the losses due to induction currents are dominant. Magnetic field H in the sample is the sum of applied magnetic field H_{ext} and the field due to the induction currents, H_{ind}.

As can be seen from Fig. 4, hysteresis loop in coordinates $B(H_{ext})$ no longer coincides with the static hysteresis loop, and the coercive force determined from it is significantly higher than the true coercive force inherent to the sample material. The area of the hysteresis loop corresponds to the energy loss per remagnetization cycle with account for losses due to sample heating by conductivity currents. As expected, the high-frequency losses in the samples of 0.18 mm sheet steel are significantly less than the losses in the 0.35-mm-thick samples.

In the course of this work we studied nine samples of bonded magnets prepared using different extrusion pressures, binder concentration, and the iron powder grade (Table 2). The largest magnetic permeability was

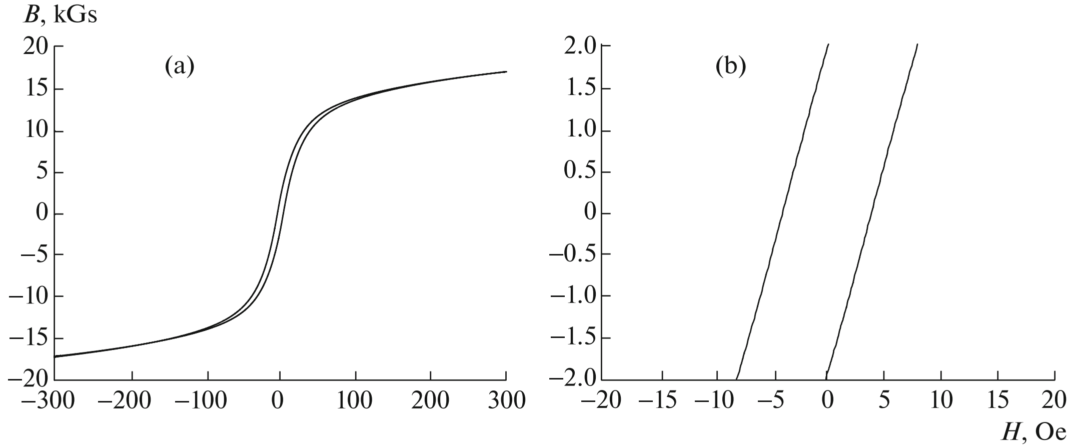

Fig. 5. The hysteresis loop of a Fe no. 2 sample without the polymer binder at a frequency of 10 Hz.

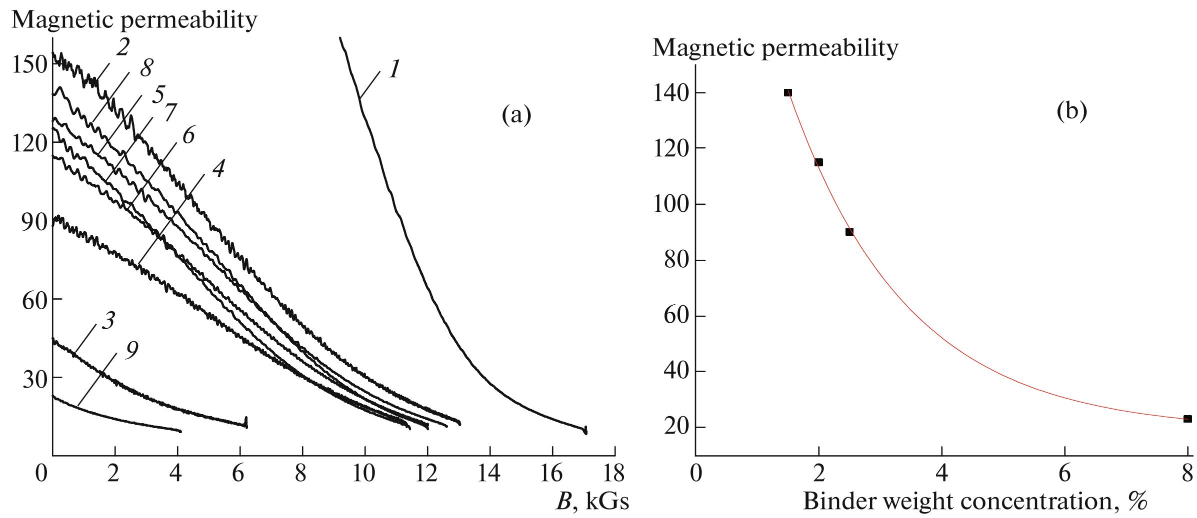

Fig. 6. The dependence of the magnetic permeability of samples on (a) the magnitude of the magnetic induction (*1*, Fe no. 2 without the binder; *2*, Fe no. 2 + 2% ER; *3*, FeSiCr + 2% ER; *4*, Fe no. 1 + 2.5% of ER; *6*, Fe no. 1 + 2% ER; *8*, Fe no. 1 + 1.5% of ER; *9*, Fe no. 1 + 3% ER + 10% TiO_2; *5*, Fe no. 1 + 2% ER; *7*, Fe no. 1 + 2% ER; samples *1–4*, *6*, *8*, *9* were obtained at an extrusion pressure of 8×10^3 kg/cm^2; *5* at 10^4 kg/cm^2; and sample *7* at 6×10^3 kg/cm^2); (b) same on the mass concentration of the binder in the samples on the basis of Fe no. 1 obtained at an extrusion pressure of 8×10^3 kg/cm^2.

found for Fe no. 2 sample, whose particles are covered with an insulating layer. This sample was prepared without an additional polymer binder at a pressure of 8×10^3 kg/cm^2. Its hysteresis loop is shown in Fig. 5a.

As can be seen from the insets to Fig. 5, the coercive force is equal to 3.9 Oe and the magnetic induction reaches a value of 16 kG in a field of 200 Oe. These values are almost identical to the corresponding values for laminated electrical steel.

Figure 6a shows dependences of the magnetic permeability on the magnetic induction determined for all samples of bonded magnets on the basis of magnetization measurements.

The maximum magnetic permeability varies from 20 to 500. All dependencies are characterized by fast decay of permeability with increasing induction.

For all of the samples prepared at a pressure of 8×10^3 kg/cm^2 from iron powder in no. 1, the dependence of the permeability on the mass concentration of the binder can be traced. The dependence is shown in Fig. 6b, where the solid line is an approximation by an exponential function.

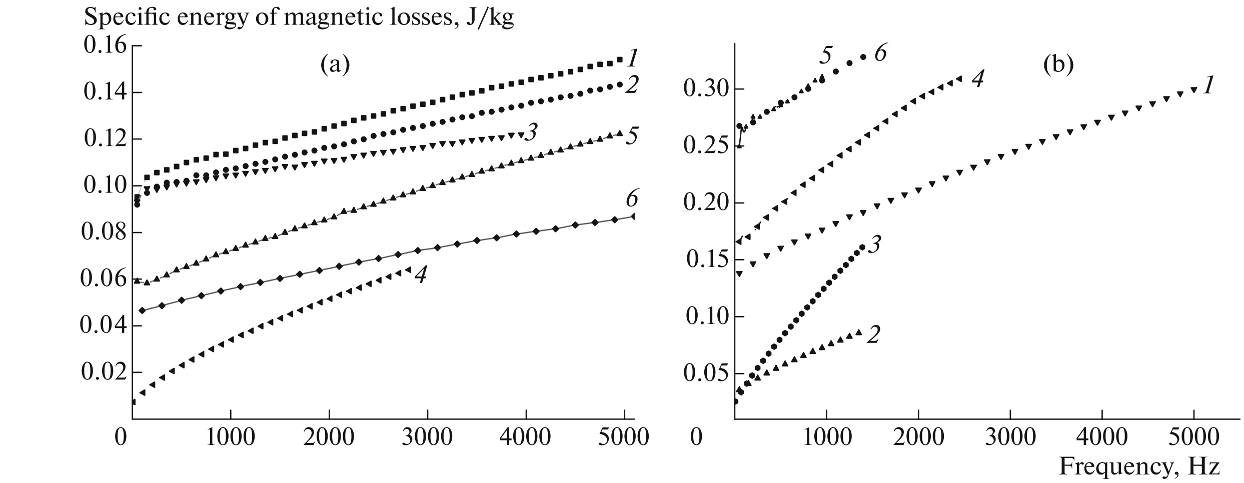

Fig. 7. The dependence of the specific energy of the remagnetization losses per period on the frequency at an induction amplitude of (a) 5 kG (*1*, Fe no. 1 + 2% ER; *2*, Fe no. 1 + 2% ER; *3*, Fe no. 1 + 2% ER; *4*, steel 2412; thickness 0.35 mm; *5*, Fe no. 2 + 2% ER; *6*, Fe no. 2 + 0% ER; samples *2*, *5*, and *6* were obtained at an extrusion pressure of 8×10^3 kg/cm^2; *1*, at 6×10^3 kg/cm^2; *3*, 10^4 kg/cm^2); (b) 10 kG (*1*, Fe no. 2 + 0% ER; *2*, grade 2421 steel; thickness 0.18 mm; *3*, grade 2412 steel; thickness 0.35 mm; *4*, Fe no. 2 + 2% ER; *5*, Fe no. 1 + 2% ER; extrusion pressure 8×10^3 kg/cm^2; *6*, Fe no. 1 + 2% ER; extrusion pressure 10^4 kg/cm^2).

3. DISCUSSION

As noted above, the losses during alternating remagnetization of soft magnetic materials are determined by two major factors, namely the losses due to magnetic hysteresis and the losses due to the Joule heat produced by Foucault currents. Both contributions are determined by different conditions of remagnetization. The hysteresis losses, as follows from the consideration of the hysteresis loop, are determined by the amplitude of the external magnetic field, whereas the losses due to the Foucault currents linearly increase with the remagnetization frequency and decrease as the resistivity of magnetic material increases. Figures 7a and 7b show the frequency dependences of the specific energy of remagnetization losses for bonded magnets and grade 2412 steel with a sheet thickness of 0.18 and 0.35 mm at a magnetic field amplitude of 5 and 10 kG, respectively.

As can be seen from Fig. 7a, the lowest magnetic losses among the bonded magnets samples are observed for the samples of the iron no. 2 powder with no epoxy binder. The iron no. 2 powder with 2% of the epoxy binder is characterized by higher losses. The samples made of the iron no. 1 powder have very close values of the magnetic losses, which depend weakly on the extrusion pressure and the amount of the binder.

The same trends are observed in Fig. 7b. Due to the significantly smaller hysteresis losses, the samples of electrical steel are characterized by substantially smaller losses in the studied frequency range up to 1.5 kHz. This is consistent with the measured values of the coercive force, which is of the order of 5 Oe for binded magnets and 0.5 Oe for electrical steels. As for the frequency-dependent part of the specific energy of remagnetization losses, all bonded magnets are characterized by a smaller fraction of the induction losses than the 0.35-mm-thick steel. The sample of bonded magnets prepared of the iron no. 2 powder without polymer binder is characterized by much lower frequency-dependent losses than the 0.18-mm-thick electrical steel. It should be noted that the magnitude of the frequency-dependent losses for bonded magnets is not in obvious correlation with their specific resistivity. As an example, a sample of iron no. 2 prepared with no binder has an order of magnitude lower resistance than a sample with 2% binder, but it is also characterized by lower frequency-dependent losses. The samples made of the iron no. 1 powder also exhibit no obvious relationship between the resistivity and the value of the frequency-dependent magnetic losses. A likely reason is that the heat losses due to the Foucault currents in the entire sample volume are much lower than the heat losses due to the Foucault currents within each powder particle. In this case, a further increase in the average specific resistance of the sample does not reduce the frequency-dependent part of the remagnetization losses and the powder particles can be considered as perfectly electrically insulated.

It should be noted that the extrapolation of curves *4* and *3* in Figs. 7a and 7b to the high-frequency region reveals some critical remagnetization frequencies at which specific losses in the 0.35-mm-thick steel are equal to the losses in the bonded magnets. At higher frequencies the remagnetization losses in the electrical steel exceed the losses in the bonded magnets.

CONCLUSIONS

Summing up the results of this work, we can conclude that it is possible to obtain isotropic magnetically soft resin-bonded magnetic materials for electrical applications with a working range of the induction values characteristic for the electrical steels of known brands, a magnetic permeability as high as 500, and high specific resistivity that reaches values of tens of Ω cm and provides a relatively low level of induction losses at frequencies of the order of a few kHz.

The samples studied in this work had a relatively high level of hysteresis losses associated with a high coercive force reaching 4–5 Oe, whereas the coercive force of electrical steels is less than 1 Oe. At the same time, currently known technological methods, including optimization of the grain size of the magnetic powder, selection of polymer binders, and heat treatment, enables a significant improvement of the magnetic properties of the bonded magnets. In any case, in specific devices magnetically soft bonded magnets can be competitive with industrial electrical steels.

ACKNOWLEDGMENTS

This work was performed with the financial support of the Ministry of Education and Science of the Russian Federation in the framework of integrated project no. 02.G25.31.0145 and the Russian Science Foundation, project no. 16-19-10508.

REFERENCES

1. O. Aglen, in *Proc. IEEE International Electric Machines and Drives Conf., Madison, USA, 2003* (IEEE, 2003), Vol. 2, p. 1117.
2. A. Krings, S. Nategh, A. Stening, et al., in *Proc. 5th Int. Conf. Magnetism and Metallurgy, Gent, Belgium, 2012*, p. 101.
3. O. G. Proselkov, Graduation Thesis (Moscow State Univ., Moscow, 2008).

Translated by V. A. Alekseev