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Physical properties of permanent magnets for magnetic circuits of electric machines

Summary — The article presents the results of physical properties investigation of bonded permanent magnets — so-called dielectromagnets. These permanent magnets Nd-Fe-B were made by bonding a hard magnetic powder with a binding agent. For purposes of this research several hard magnetic powders were selected. Hard magnetic powders were obtained from melt-spun ribbon of Nd-Fe-B alloy. The physical properties of sintered magnets from groups such as: ferrite, Nd-Fe-B and Sm-Co were also measured.
Keywords: dielectromagnets, bonded magnets, electric motors, magnetic properties, mechanical properties, electrical properties.

WŁAŚCIWOŚCI FIZYCZNE MAGNESÓW TRWAŁYCH PRZEZNACZONYCH DO OBWODÓW MAGNETYCZNYCH MASZYN ELEKTRYCZNYCH

Streszczenie — W artykule przedstawiono wyniki badań właściwości fizycznych wiązanych magnesów trwałych tzw. dielektromagnesów. Dielektromagnesy Nd-Fe-B wytwarzano poprzez spojenie proszku magnetycznie twardego za pomocą substancji spajającej. Proszek magnetycznie twardy otrzymywano z taśmy powstającej z szybko chłodzonego stopu Nd-Fe-B. Przeprowadzono również badania właściwości fizycznych spiekanych magnesów trwałych takich jak: magnesy ferrytowe, samarowo kobaltowe Sm-Co oraz magnesy neodymowe Nd-Fe-B.
Słowa kluczowe: dielektromagnesy, magnesy wiązane, silniki elektryczne, właściwości magnetyczne, właściwości mechaniczne, właściwości elektryczne.

INTRODUCTION

Manufacturers of electrical machines and other electromagnetic and electromechanical transducers are looking for methods to reduce production costs. Isotropic nature of the bonded magnets allows obtaining a multipolar distribution of magnetic poles. In many cases it is possible to avoid gluing of the magnets. Dielectromagnets from Nd-Fe-B melt-spun ribbon have good magnetic properties. They fill the gap between low-cost ferrite magnets with poor magnetic properties and expensive sintered magnets Sm-Co or Nd-Fe-B with very good magnetic properties.

Permanent magnets are commonly used in structures of electric motors as the excitation source. According to their production technology, permanent magnets can be divided into groups such as: sintered magnets, cast magnets and bonded magnets (so-called dielectromagnets). Dielectromagnets made from melt-spun ribbon of Nd-Fe-B alloy are manufactured using the powder metallurgy technology. In this case hard magnetic powder is bonded by a bonding agent. The mixture of hard magnetic powder with bonded substances is put in a die and pressed in a hydraulic press. After finishing this process, hard magnetic material is cured in a heat chamber. The next step is magnetization. Dedicated magnetization fixtures are used to obtain the required distribution of magnetic poles on the surface of the permanent magnet.

Isotropic Nd-Fe-B dielectromagnets can be magnetized in various directions. The configuration of magnetic poles can be tailored according to the requirements of designers of the electric motor. The advantages of this type of permanent magnets are as follows: good magnetic characteristics, simple production technology (much less sophisticated than the production technology of sintered magnets) and the possibility of adjusting the physical properties to the design requirements of electric machines. Using the powder metallurgy technology allows manufacturing of dielectromagnets of complex shapes and precise dimensions without further machining. Dielectromagnets are also recycling-friendly. Designers of electric motors require that it should be possible to tailor the physical properties of permanent magnets. Physical properties of materials, which are used for magnetic circuits,

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influence the efficiency of electric machines [1—10]. During the investigation magnetic, mechanical and electrical properties of selected permanent magnets were tested.

For purposes of testing the following magnets were selected: dielectromagnets from nanocrystalline Nd-Fe-B powder from melt spun ribbon, sintered magnets from Nd-Fe-B alloy, Sm-Co alloy and sintered ferrite magnets. Sintered magnets were selected from the commercially available range. In the case of bonded magnets the appropriate research on the impact of production technology on their physical properties was also conducted. A part of the research concerned bonded magnets made of hard magnetic powder, modified in order to improve their physical properties.

The aim of the research is to create a knowledge base of bonded and sintered permanent magnets including information about physical properties of various hard magnetic materials. The main goal of the research is to acquaint designers of electric motors with permanent magnets with their various physical properties. Thanks to this, they will be to choose permanent magnets with optimal properties for a given construction of electric motor.

EXPERIMENTAL

Materials

Magnetic powders, listed in Table 1, were selected for experiments. Other substances used in our experiments are characterized in Table 2.

T a b l e 1. Characteristics of hard magnetic powders selected for experiments

Name	Producer	Composition	Temperature coefficient of B_r, %/ °C	Temperature coefficient of H_{cJ}, %/ °C	Curie temperature T_c, °C	Maximum operating temperature, °C	Density (theoretical) g/cm^3
MQP-B 10184-0790	Magnequench	Nd-Co-Fe-B	-0.11	-0.40	360	120—160	7.64
NQP-A	Yuxiang Magnetic Material Co.	Nd-Fe-B	-0.13	-0.40	310	120	7.60
NQP-B			-0.105	-0.40	390	120	7.64
NQP-C			-0.07	-0.40	470	150	7.64
NQP-D			-0.07	-0.40	470	150	7.64
NQP-L			-0.048	-0.35	400	100	7.40

T a b l e 2. Characteristic of additional substances selected for magnets preparation

Name	Function	Producer	Form	Characteristics				
Epidian 100	bonding substance	Organika Sarzyna	powder epoxy resin	curing temperature: 130—190 °C curing time: 4h at 150 °C and 50 min at 190 °C				
Zinc Stearate	lubricant	Polskie Odczynniki Chemiczne	powder	$Zn(C_{18}H_{35}O_2)_2$				
Silquest A-1100	silane	Momentive Performance Materials	liquid	$H_2N(CH_2)_3Si(OCH_2CH_3)_3$				
				SiO_2 content, %	silanol groups content, %	degree of crosslinking %	phenyl/ methyl molar ratio	molecular weight
DC217	solid polymeric resins	Dow Corning Corporation	flakes	47	6	75	—	1500—4000
DC220				52	1	70	2.0 / 1	2000—4000
DC249				63	5	71	0.6 / 1	2000—4000

In order to investigate the physical properties of sintered magnets, commercially available permanent magnets were selected. The physical properties of sintered ferrite magnets type F30, sintered Nd-Fe-B type N38, sintered $SmCo_5$ type S18 and Sm_2Co_{17} type S30 were measured.

Sample preparation

Dielectromagnets

In order to investigate the effect of sample preparation method on physical properties of bonded permanent magnets several series of samples were prepared. In each series samples were divided according to the value of one of the parameters of the manufacturing process: pressing pressure, curing temperature, curing time and content of the bonding substance. Designation of samples obtained using various values of mentioned parameters are presented in Table 3.

T a b l e 3. Parameters of production technology and corresponding symbols for samples of dielectromagnets

Symbol of sample	Parameters of production technology		
A1	change of the compression pressure	180 °C, 2h	900 MPa
A2		2.5 wt. % of Epidian 100	800 MPa
A3		0.2 wt. % of zinc stearate	700 MPa
B1	change of the hardening temperature	900 MPa, 2h	200 °C
B2		2.5 wt. % of Epidian 100	180 °C
B3		0.2 wt. % of zinc stearate	160 °C
C1	change of the hardening time	900 MPa, 180 °C	4h
C2		2.5 wt. % of Epidian 100	3h
C3		0.2 wt. % of zinc stearate	2h
D1	change of the Epidian 100 content	900 MPa,180 °C, 2h	3.5 wt. %
D2		0.2 wt. % of zinc stearate	2.5 wt. %
D3			1.5 wt. %

Dielectromagnets made from powder after the silanization process

Another area of research is an attempt to improve the physical properties of dielectromagnets by modifying the surface of hard magnetic powder. This modification consists in coating the grains of powder with a substance increasing the capacity of the hard magnetic material to bind with a binding agent and facilitates the pressing process. The material which covers the powder particles is silane, and the process of imposing its layers is referred to as silanization. Silanization of hard magnetic powders was performed in the Industrial Chemistry Research Institute (IChP). Hard magnetic powder type MQP-B was subjected to silanization with silane A-1100. Test samples were dielectromagnets made of the silanized powders. Dielectromagnets were made using the parameters of technological process specified in Table 4. As a bonding material epoxy resin Epidian 100 (E-100) was used.

T a b l e 4. Parameters of production technology and corresponding symbols for samples made from powder after silanization process

Symbol of samples	Parameters of production technology		
	material	content of silane and resin, wt. %	pressing pressure, hardening temperature, hardening time
E1	A-1100	0.5	900 MPa, 180 °C, 2h
	DC217	1.49	
E2	A-1100	0.5	
	DC220	1.49	
E3	A-1100	0.5	
	DC249	1.49	
F1	A-1100	0.5	900 MPa, 180 °C, 2h
	E-100	0.48	
	DC-217	1.02	
F2	A-1100	0.49	
	E-100	0.47	
	DC220	1.00	
F3	A-1100	0.5	
	E-100	0.48	
	DC249	1.02	
F4	A-1100	0.5	
	E-100	1.5	

Method of testing

Prepared samples of permanent magnets were tested by determination of magnetic mechanical and electrical properties. In Table 5 are collected information about methods and devices used in these investigations. For measurements of each physical property of magnets the samples with dimensions given in Table 6 were prepared.

T a b l e 5. Kind of measurement, measurement method and standards applied for physical properties measurements

Kind of measurement	Measurement method	Standards	Physical properties
metallography	Scanning electron microscope (SEM)		particle size, surface and structure of powders
magnetic properties	Hysteresisgraph AMH – 20K-HS Laboratorio Elettrofisico	IEC 60404-5	B_r — residual induction, T H_{cJ} — coercivity of magnetic polarization, kA/m H_{cB} — coercivity of magnetic induction, kA/m $(BH)_{max}$ — maximum energy, kJ/m^3
mechanical properties	Universal testing device 1115 Instron	PN-H-04942:1986 PN-H-04947:1976 PN-EN ISO 2740:2002	R_c — compressive strength, MPa R_g — transverse rapture strength, MPa R_m — testing tensile strength, MPa
	Fritz Heckert 308 / 356	PN-EN ISO 6506-1	*HB* — Brinell hardness
	d = weight/volume		*d* — density, g/cm^3
electrical properties	four-lead method	PN-C-82055/08:1990	ρ — resistivity, μΩ·m

T a b l e 6. Dimensions of samples used for measurements

Kind of measurement		Dielectromagnets	Sintered magnets		
			F30 Ferrite	Nd-Fe-B N38	Sm-Co S18 S30
		Dimensions, mm			
magnetic properties		∅ 10 × 4	∅ 10 × 5	∅ 10 × 5	∅ 10 × 4
mechanical properties	density	∅ 10 × 4	∅ 10 × 5	∅ 10 × 5	∅ 10 × 4
	compressive strength	∅ 10 × 14	∅ 10 × 5	∅ 10 × 5	∅ 5 × 7
	transverse rupture strength	30 × 12 × 6	24.5 × 9.85 × 6	30 × 10 × 5	30 × 12 × 6
	testing tensile strength	Length of sample: 90	—	—	—
electrical properties		76 × 12 × 6	—	—	—

Due to the limited range of shapes and dimensions of sintered permanent magnets not all their parameters were determined. Research was focused on measuring magnetic properties and mechanical strength, such as compressive strength and bending strength. Due to the high strength of the sintered magnets, the compressive strength tests were performed on cylindrical samples with a smaller than typical diameter.

RESULTS AND DISCUSSION

Metallography

Metallography pictures allow researchers to compare particle size, surface and structure of various powders. The study provides an important set of information, useful in finding new ways to improve physical properties of dielectromagnets. Figure 1 presents examples of metallographic images of powders selected for the study. The pictures demonstrate differences between various types of powder. Powder of type NQP-B has smaller grains and a different type of grain surface than powder MQP-B. After the silanization process the layers of silane on the grains are irregularly distributed.

Magnetic properties

Table 7 presents the magnetic parameters of samples manufactured from MQP-B powder. The results of this study suggest that parameters of the production techno-

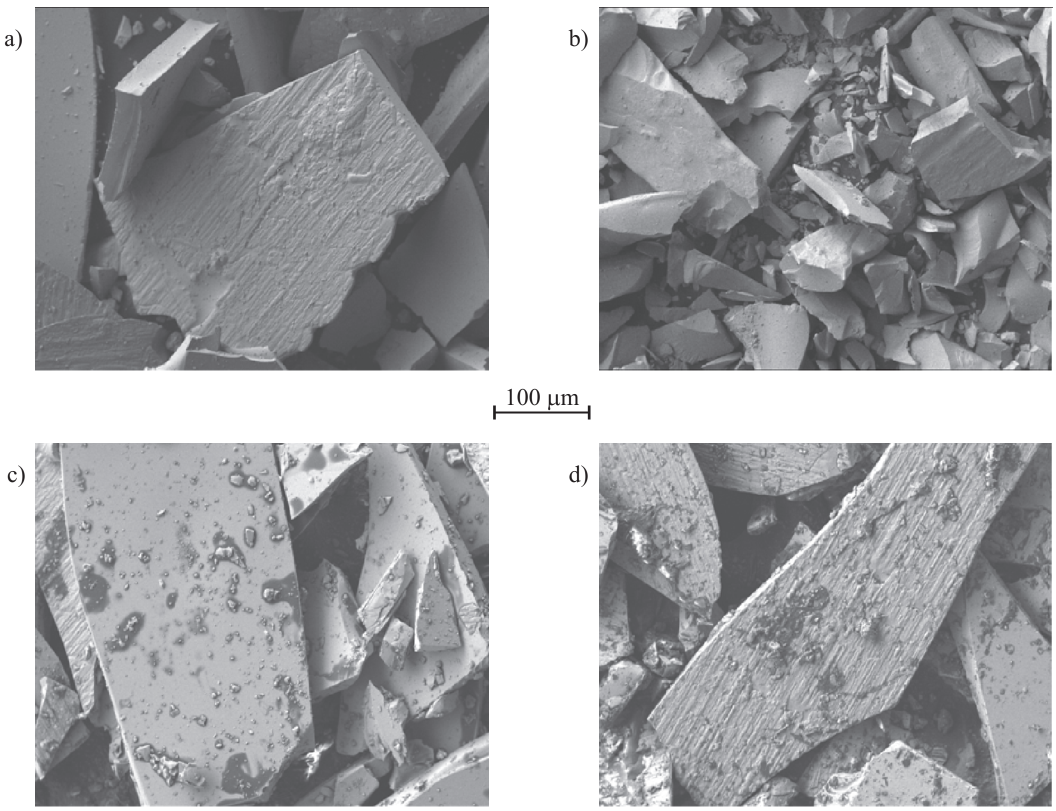

Fig. 1. SEM metallographic images of Nd-Fe-B powders, zoom x 250: a) MQP-B powder, b) NQP-B powder, c) MQP-B powder after silanization with silane A-1100 and coated with solid silicone resin DC217, d) MQP-B powder after silanization with silane A-1100 and coated with solid silicone resin DC220

logy have a significant effect on the magnetic properties of dielectromagnets. The maximum density of magnetic energy was obtained in the case of sample D3 pressed at pressure of 900 MPa (parameters of curing process: time 2h, temperature 180 °C, content of bonding substance: 1.5 %). Increase in the content of bonding resin in the mixture leads to a decrease in its magnetic properties. Table 8 presents the magnetic parameters of samples manufactured from NQP-B powder. Dielectromagnets made of NQP-B powder have worse magnetic properties than dielectromagnets manufactured from MQP-B powder. Optimal parameters of the production technology are as follows: pressing pressure 900 MPa, curing temperature and time 180 °C and 2h, content of bonding substances 2.5 %.

T a b l e 7. Results of measurements of magnetic properties for samples manufactured from MQP-B powder

Symbol of sample	d g/cm^3	B_r T	H_{cJ} kA/m	H_{cB} kA/m	$(BH)_{max}$ kJ/m^3
A1	5.83	0.671	681.60	423.9	71.83
A2	5.79	0.646	661.72	404.97	63.96
A3	5.77	0.648	652.07	405.75	64.83
B1	5.86	0.644	621.50	394.1	61.35
B2	5.83	0.671	681.60	423.9	71.83
B3	5.88	0.639	672.83	407.83	63.95
C1	5.89	0.670	662.15	408.90	71.42
C2	5.87	0.646	649.84	403.69	64.61
C3	5.83	0.671	681.60	423.9	71.83
D1	5.77	0.637	705.00	423.28	66.94
D2	5.83	0.671	681.60	423.9	71.83
D3	5.89	0.706	676.48	435.51	75.33

T a b l e 8. Results of measurements of magnetic properties for samples manufactured from NQP-B powder

Symbol of sample	d g/cm^3	B_r T	H_{cJ} kA/m	H_{cB} kA/m	$(BH)_{max}$ kJ/m^3
A1	5.95	0.617	686.4	388.2	60.57
A2	5.92	0.617	691.9	389.8	60.79
A3	5.87	0.612	699.1	390.1	60.40
B1	5.97	0.617	673.9	382.2	59.23
B2	5.95	0.617	686.4	388.2	60.57
B3	5.97	0.619	693.7	391.9	61.48
C1	5.96	0.617	681.4	385.9	60.14
C2	5.94	0.615	682.5	385.6	60.18
C3	5.95	0.617	686.4	388.2	60.57
D1	5.82	0.605	691.9	385.8	59.31
D2	5.95	0.617	686.4	388.2	60.57
D3	6.07	0.637	730.2	400.0	64.04

Table 9 shows the results of measurements of magnetic properties for samples made of NQP-A, NQP-C, NQP-D, NQP-L powders.

T a b l e 9. Results of measurements of magnetic properties for samples made of NQP-A/C/D/L powder

Kind of powder	d g/cm^3	B_r T	H_{cJ} kA/m	H_{cB} kA/m	$(BH)_{max}$ kJ/m^3
NQP-A	5.99	0.603	663.5	379.6	57.29
NQP-C	5.93	0.623	670.8	398.5	62.88
NQP-D	5.94	0.644	654.7	406.5	67.09
NQP-L	5.83	0.789	233.5	193.3	45.47

The results of the study indicate that by changing parameters of the technological process it is possible to tailor the magnetic properties of dielectromagnets. Pressing pressure of 900 MPa makes it possible to obtain dielectromagnets with very good magnetic properties. In the case of samples made of NQP-B powder increase in the time and temperature of the hardening process causes a decrease in the density of maximum energy [$(BH)_{max}$]. Magnetic parameters of dielectromagnets can be improved by reducing the content of the bonding substance. The pressing pressure and the amount of bonding substances have a significant impact on the density of hardened components. Studies have shown that dielectromagnets manufactured from NQP powders display worse magnetic properties than dielectromagnets manufactured from MQP-B powder.

Measuring the physical properties of dielectromagnets manufactured from powder after silanization was also a part of the research. Results of measurements of magnetic properties for samples manufactured from MQP-B powder, after silanization are presented in Table 10. In the case of dielectromagnets made from silanized powder, a very good value of maximum energy $(BH)_{max}$ was obtained. In the best case this value was 80.95 kJ/m^3. Silanization can improve the magnetic properties of dielectromagnets.

T a b l e 10. Results of measurements of magnetic properties for samples manufactured form MQP-B powder after silanization process

Symbol of sample	d g/cm^3	B_r T	H_{cJ} kA/m	H_{cB} kA/m	$(BH)_{max}$ kJ/m^3
E1	5.91	0.705	767.3	452.67	79.33
E2	5.87	0.705	742.0	455.43	80.27
E3	5.8	0.698	744.4	453.77	79.44
F1	5.79	0.710	738.4	454.2	80.95
F2	5.73	0.733	628.8	323.3	72.71
F3	5.77	0.705	732.9	450.1	79.26
F4	5.75	0.702	728.5	440.2	76.5

Table 11 presents the results of measurements of magnetic properties for sintered magnets. Sintered ferrite magnets have poor magnetic properties, but permanent magnets from this group are inexpensive. Expensive Nd-Fe-B sintered permanent magnets have the highest value of $(BH)_{max}$. Bonded permanent magnets have the optimal ratio of magnetic parameters to the price of a magnet.

T a b l e 11. Results of measurement of magnetic properties of sintered magnets

Material	d g/cm^3	B_r T	H_{cJ} kA/m	H_{cB} kA/m	$(BH)_{max}$ kJ/m^3
Strontium ferrite	4.81	0.388	229.2	224.8	28.68
Nd-Fe-B	7.43	1.212	976.9	868.2	265.05
$Sm\text{-}Co_5$	8.36	0.882	1598.1	584.9	128.37
$Sm_2\text{-}Co_{17}$	8.48	1.082	>1600	839.8	227.17

Mechanical properties

The main parameters of permanent magnets are their magnetic properties, but very often mechanical properties are also very important. Permanent magnets glued on the rotor are exposed to centrifugal forces and require increased mechanical strength.

In Table 12—14 there are listed the results of measurements of mechanical properties for samples manufactured from MQP-B, NQP-B and from NQP-A, NQP-C, NQP-D, NQP-L powder, respectively.

T a b l e 12. Results of measurements of mechanical properties of dielectromagnets manufactured from MQP-B powder

Symbol of sample	HB	R_c, MPa	R_g, MPa	R_m, MPa
A1	61	167.33	61.7	27
A2	59	164	59	26.5
A3	55	156	55.9	28.9
B1	62	178.33	66.8	31
B2	61	167.33	61.7	27
B3	62	158	64.3	25.7
C1	59	158	58.7	30.4
C2	64	166.33	67.9	30.1
C3	61	167.33	61.7	27
D1	70	203.33	78.1	39
D2	61	167.33	61.7	27
D3	45	106.33	39.7	13.3

These results show that by changing parameters of the technological process mechanical properties of dielectromagnets can be tailored. A higher pressing pressure, a higher curing temperature and higher contents of the bonding substance lead to an increase in mechanical properties of dielectromagnets. Pressing pressure and content of bonding substance have a significant impact on the hardness of dielectromagnets.

T a b l e 13. Results of measurements of mechanical properties of dielectromagnets manufactured from NQP-B powder

Symbol of sample	HB	R_c, MPa	R_g, MPa	R_m, MPa
A1	73	179.7	66.0	38
A2	70	175.0	66.0	38
A3	51	166.0	64.4	34
B1	67	189.3	70.3	40
B2	73	179.7	66.0	38
B3	75	173.0	60.8	34
C1	69	184.3	62.1	34
C2	60	185.7	66.4	33
C3	73	179.7	66.0	38
D1	67	198.7	85.0	47
D2	73	179.7	66.0	38
D3	48	113.3	45.6	23

T a b l e 14. Results of measurements of mechanical properties of dielectromagnets manufactured from NQP-A/C/D/L powder

Kind of powder	HB	R_c, MPa	R_g, MPa	R_m, MPa
NQP-A	83	188.67	66.9	28
NQP-C	65.8	173.0	65.8	39
NQP-D	63.1	176.0	63.1	37.5
NQP-L	61.4	156.0	61.4	39.5

T a b l e 15. Results of measurements of mechanical properties for samples manufactured from MQP-B powder after silanization process and coated with silicone resin

Symbol of sample	HB	R_c, MPa	R_g, MPa	R_m, MPa
E1	11.9	34	2.6	Samples too brittle
E2	9.3	37.33	2.9	
E3	13.9	33.67	3.1	
F1	14.5	31.33	3.8	1.3
F2	13	28.5	3.8	0.8
F3	11.1	32.5	3.9	1.7
F4	13.2	13.5	3.1	0.8

Results of measurements of mechanical properties for samples manufactured from MQP-B powder after silanization process are presented in Table 15. In case of several samples of dielectromagnets, it was not possible to measure their mechanical strength. Several samples of dielectromagnets were damaged during the manufacturing process. The samples were brittle and easily cracked.

Mechanical properties of dielectromagnets manufactured from powders after silanization are much worse than mechanical properties of dielectromagnets manufactured from MQP-B powder without silanization.

T a b l e 16. Results of measurement of mechanical properties of sintered magnets

Material	R_c, MPa	R_g, MPa
Strontium ferrite	960	149
Nd-Fe-B	959	258
$Sm\text{-}Co_5$	1855	64.6
$Sm_2\text{-}Co_{17}$	796	94

Table 16 presents results of measurements of mechanical properties for sintered magnets. To investigate the mechanical properties of sintered magnets commercially available magnetic materials (with dimensions and shapes according to the standards) were selected. Due to the sintered permanent magnets' limited range of shapes and dimensions not all parameters were determined.

Electrical properties

Table 17 shows the results of resistivity measurements for samples manufactured from MQP-B powder. High value of resistivity reduces eddy current losses. This is very important, for example, in magnetization process. Dielectromagnets with high resistivity require that the current powering the magnetization fixtures should be low. Table 18 shows the resistivity values for samples manufactured from NQP-B powder and Table 19 for similar samples manufactured from NQP-A, NQP-C, NQP-D and NQP-L powder. The results show that the resistivity depends to a large extent on the content of bonding substance. When the mixture has higher content of bonding substance, the dielectromagnets have higher resistivity. In the case of the magnet made of NQP-B powder with content of 3.5 wt. % of Epidian 100, the resistivity of the sample is about 73 μΩ · m.

T a b l e 17. Results of measurements of resistivity of dielectromagnets manufactured from MQP-B powder

Symbol of sample	ρ, μΩ · m
A1	39
A2	44
A3	50
B1	37
B2	39
B3	37
C1	37
C2	39
C3	39
D1	35
D2	39
D3	30

T a b l e 18. Results of measurements of resistivity of dielectromagnets manufactured from NQP-B powder

Symbol of sample	ρ, μΩ · m
A1	49
A2	62
A3	68
B1	53
B2	49
B3	55
C1	47
C2	54
C3	49
D1	73
D2	53
D3	39

T a b l e 19. Results of measurements of resistivity of dielectromagnets manufactured from NQP-A/C/D/L powder

Kind of powder	ρ, μΩ · m
NQP-A	49
NQP-C	50
NQP-D	53
NQP-L	61

T a b l e 20. Results of measurements of resistivity for samples manufactured from MQP-B powder after silanization process and coated with a silicone resin

Symbol of sample	ρ, μΩ · m
E1	33
E2	45
E3	45
F1	50
F2	92
F3	53
F4	107.5

The resistivity values of dielectromagnets manufactured from MQP-B powder after silanization are listed in Table 20. A large majority of samples have good value of resistivity, but in some cases a very high values were obtained. For example in the case of sample F4 value of resistivity is 107 μΩ · m. By adjusting the parameters of silanization it is possible to tailor the value of resistivity of dielectromagnets.

CONCLUSIONS

The parameters of the production technology of dielectromagnets have significant influence on their physical properties. This applies to the type and content of binding material, as well as to the pressing pressure and parameters of the hardening process.

The results of research indicate that dielectromagnets manufactured from MQP-B powder have better magnetic properties than dielectromagnets manufactured from NQP powders. However, dielectromagnets manufactured from MQP-B powder have smaller values of other parameters such as mechanical strength, hardness, density and resistivity. Powder metallurgy technology makes it possible to tailor the physical properties of dielectromagnets. This means that magnetic properties can be increased at the expense of mechanical properties.

At the present stage of research relating to the improvement of physical properties, as a result of performed silanization, a better value was obtained — in comparison with the MQP-B powder — for magnetic parameters, density and resistivity. However, dielectromagnets manufactured from powder after silanization have too small mechanical strength, which limits their practical application. Development of the type and amount of additional substances necessary to improve the physical properties of dielectromagnets requires further research.

The results of the research presented create a knowledge base about physical properties of permanent magnets. A database of information allows the proper selection of hard magnetic materials to be used in a new generation of electric devices.

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