STRUCTURING SOFT-MAGNETIC COMPOSITE MATERIALS

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Abstract: The aim of the proposed paper is to present different procedures for preparation the mixture of soft-magnetic powder material and to show the influence of different manufacturing processes for achieving particular structures and properties of soft magnetic composite (SMC) material. The technique of SMC production with improved mechanical properties and the necessary electrical and magnetic parameters by means of powder metallurgy methods are described. A novel laminated powder structure of SMC material is developed. The content of the paper gives useful hints for specialists dealing with creation and research of new magnetic materials and magnetic systems for electric machines and power electronics.

Strukturiranje mehkomagnetnega kompozitnega materiala

Kjučne besede: Metalurgija prahov, mehko-magnetni kompozitni material, histerezne izgube, vrtinčne izgube, izgube v železu

Izvleček: V članku so predstavljeni različni načini priprave mešanice mehkomagnetnih prahov z dodatki in vplivi različnih tehnoloških postopkov izdelave na končne lastnosti mehkomagnetnih kompozitnih (MMK) materialov. Predstavljen je merilni sistem, ki omogoča določanje magnetnih lastnosti MMK materiala. Opisane so tudi lastnosti nove lamelirane strukture MMK materiala. Vsebina članka podaja koristne napotke specialistom, ki se ukvarjajo z ustvarjanjem in raziskovanjem novih magnetnih materialov ter elektromagnetnih sklopov za elektične stroje in močnostno elektroniko.

1. Introduction

Soft-magnetic composites, i.e. ferromagnetic material in the powder form are mainly made by atomization of Fe-Si compound. The material is mostly used for electric micro and small machine cores /1, 2/ and in power electronic for inductor cores. The powder can be pressed to the required shape and thus forming a magnetic core of desired geometric properties.

The world production of soft-magnetic composites is limited, which results in a relatively high material cost. The price is lower regarding the 0.1 mm laminated steel, but higher as that of 0.5 mm laminated steel, traditionally used in electric machines manufacturing /3-7/.

Existing production techniques ensure the required properties and characteristics of soft-magnetic composite materials due to high quality of expensive primary materials – iron powders and bonding materials, which causes a significant increase of their cost. That is why development of high-quality soft-magnetic materials and decrease of their production cost is a prospective direction of the study /8, 9/.

The objective of this analysis is to improve the method of manufacturing the soft-magnetic composites samples with the required mechanical, electrical and magnetic characteristics. That include magnetic saturation B_s, residual magnetization B_R, coercive force H_c, electric conductivity, iron losses Pm, mechanical strength and compactness. Taking into consideration the range of change of the analyzed parameters, it is necessary that the measuring equipment and methods of processing the measurement results take into account nonlinear properties of the magnetic material. The measurements must achieve assigned accuracy in a wide range of parameters change, including the condition of high saturation level. In this way the magnetic measurements carried out during researching are different from measurements performed throughout normative testing or during the production monitoring.

2. Preparation and fabrication of soft magnetic composite material

Taking into account the peculiarities of the soft-magnetic material structure, a sequence of the main cycles of manufacturing technique by means of powder metallurgy is summarized:

1. Powder is produced by means of an electrolytic method, which provides high powder dispersion and well-developed dendrite shape of grain particles.
2. Preparation of powders for pressing, which includes their pre-firing at the temperature of 250-350^{0}C, formation of a powder sieve structure with preset fractional dimensions, then mixing it with a lubricant and plastic bonding material ensuring maximum electrical isolation between ferromagnetic grains. Powder sieve structure is analogous to the one stated in /10, 11/.
3. Warm pressing under controlled pressure and temperature of 200-450^{o}C, which enables plastic bonding material to cover the grain surface uniformly and to electrically insulate the grains between each other. The process of this stage also influences the formation of the grain structure into final product shape.

   In the frame of our research we made some specimens of SMC material in the form of rings. The rings were prepared for microscopic analysis and some of the results are presented below. Separate grains of different size (10÷20 μm) are visible in Fig. 1. The grains are separated with inclusions layer. The separation blisters are visible, but the additives are not observed. The separate sintered grains (5÷20 μm) and alloyed or sintered grains without a separating interlayer are also shown in Fig. 2.

4. Annealing at temperatures of 1150-1250^{0}C provides formation of the necessary grain structure in the product and ensures the required mechanical, electrical and magnetic properties of the soft-magnetic composite structure.

For each of the mentioned cycles there are only general recommendations due to a wide range of parameters variation and different modes of performing the cycles. The task of our research is to select of all the parameters, beginning with the ones which influence the analyzed characteristics. This mainly refers to the second and fourth cycle. During the preparation for the pressing cycle the research should be focused on iron powder compositions, choice of the plastic bonding material and a lubricant to improve the necessary mechanical properties, as well as electrical and magnetic parameters. In case of high-temperature annealing it is also necessary to exactly measure the specimen temperature and cycle duration.

Further results were obtained by annealing the specimen at the temperature of 220^0 C. The texture of soft magnetic iron-based sample was made in this way. Uniform distribution of plastic bonding material on the grains surface was revealed (Fig. 3) by scanning the sample. The X-ray spectrum analysis of specimen (Fig. 4) shows that the electric isolation layer is spread uniformly across the grain surface. The results are presented in Fig. 4. This insulation layers decrease electric conductivity of the material and reduce induced eddy currents.

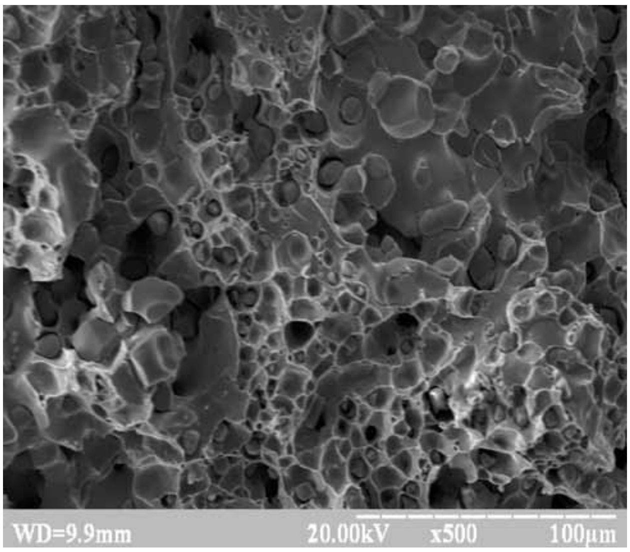

Fig. 1: Separate grains of different size (10÷20 μm) with inclusions layer

Metallographic analysis was made using NIAPHOT-2 microscope (France). Fracture investigation was made by REM-106I focused beam electronic microscope (Sumy, Ukraine).

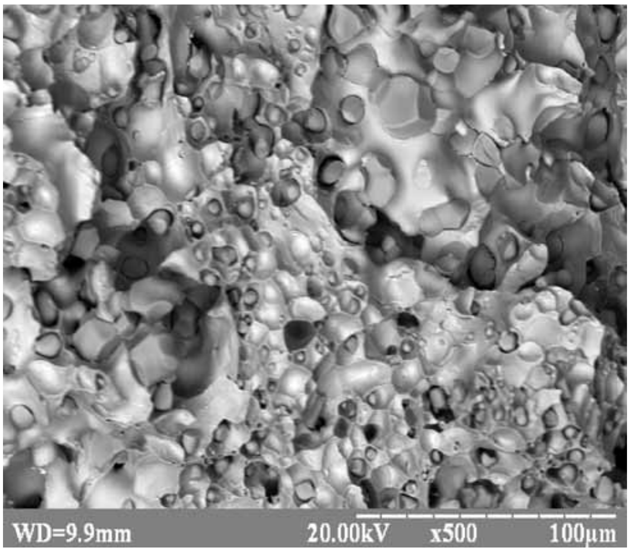

Fig. 2: The separate sintered grains 5÷20 micrometers and alloyed or sintered grains without separating interlayer.

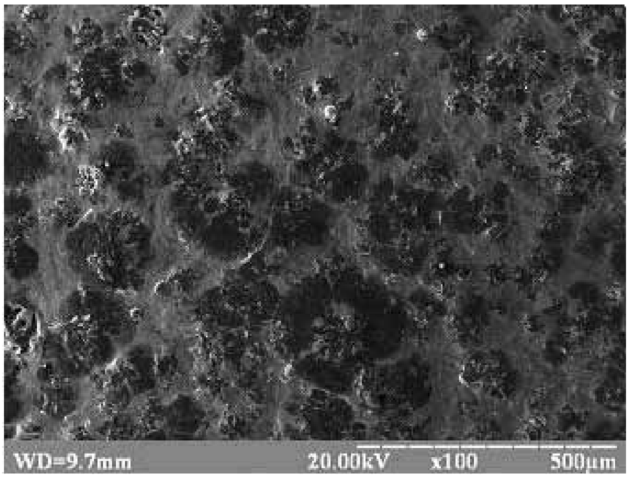

Fig. 3: Uniform distribution of plastic bonding material on the grains surface

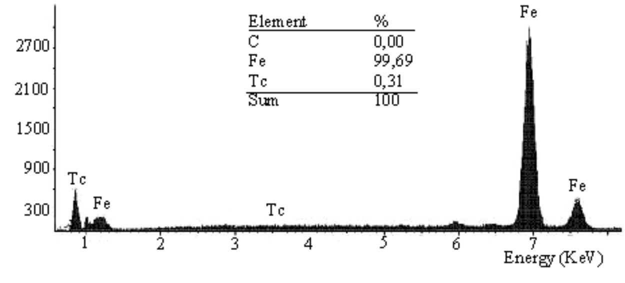

Fig. 4: The X-ray spectrum analysis of a specimen

3 Measuring system

Regarding the requirements of testing equipment /12/, the use of inductive measuring procedure with alternating magnetization of samples with changing amplitude and frequency is the most reasonable one.

The structure of the measuring system (MS) is shown in Fig. 5. A tested sample (TS) represents a closed magnetic system with magnetization and measuring windings. The parameters which characterize the testing system are: current $i_1(t)$, voltages $u_1(t)$ and $u_2(t)$. The signals from TS go to current CT and voltage VT2 transducers. Output signal $u_1(t)$ from off-line sinusoidal voltage source (PS) is connected to the voltage transducer VT1 and to the tested sample.

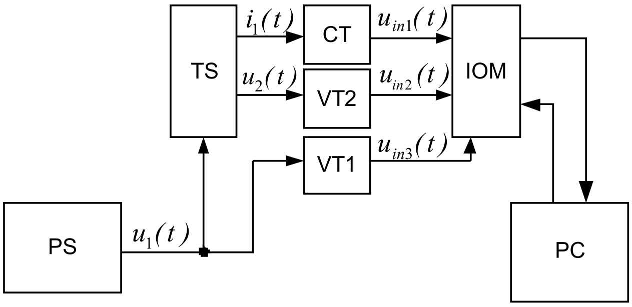

Fig. 5: Block diagram of the measuring system for testing soft-magnetic composite material samples

Signals from the transducers go through input/output module (IOM) to a computer, whose functions are data gathering, storage and processing. The offered MS uses certified testing module E14-440D (L-Card, Russia) as an IOM. Measuring software is realized in software environment Lab View 8.2 with the aim to achieve the reconfiguration flexibility and visualization of measurement process.

Due to magnetization of soft-magnetic material in alternating magnetic fields the determination of the magnetic flux density $B(t)$ and the magnetic field strength $H(t)$ frequency spectrum from the linear section of magnetization up to the saturation level is required. Also, the conditions of frequency spectrum decomposition and further composition have to be formulated.

Taking into consideration the above described peculiarities of the test, the determination of all the parameters was established on the base of preliminary decomposition of the measured signals applying Fourier transform. The results are used to compute the necessary parameters, such as magnetic flux density, magnetic field strength, hysteresis losses and eddy current losses.

The amplitude of magnetic flux density is calculated by:

$$B_m = \frac{\sqrt{2}}{2\pi}\frac{U_2}{f\,N_{ms}\,S_c}, \qquad (1)$$

where U_2 is the effective value of measuring winding voltage; N_{ms} – number of measuring winding turns; S_c – magnetic circuit core cross-section area; f – magnetization frequency.

Magnetic field strength is computed by:

$$H = I_1 N_{mg} / l \qquad (2)$$

where I_1 is the effective value of current in magnetizing winding, N_{mg} is the number of magnetizing winding turns and l is the average length of magnetic circuit.

If $B(t)$ and $H(t)$ are not sinusoidal at a linear section of magnetization curve, the computation is carried out only on the basis of the first harmonic components. Total harmonic distortion of signals is estimated with the help of current $i_1(t)$ and voltage $u_2(t)$ harmonic factor:

$$k_h = \sqrt{\sum_{p=2}^{k} A_p^2} \Big/ A_1, \qquad (3)$$

where p is the higher harmonic number, k is the number of the considered harmonics, A_1 and A_2 are, correspondingly, effective values of the first and p-th order harmonics in signal.

Losses in magnetic material are derived by

$$P_{q\mu p} = \frac{N_{mg}}{N_{ms}}(a_{i1p}a_{u2p} + b_{i1p}b_{u2p})/4, \qquad (4)$$

Where a_{i1p}, b_{i1p}, a_{u2p} and b_{u2p} are, correspondingly, current $i_1(t)$ and voltage $u_2(t)$ signals squared components.

After processing the measured values $i_1(t)$ and $u_2(t)$ a dynamic hysteresis loop is created. Instantaneous value of the magnetic field strength is found from the relation

$$H(t) = i_1(t) N_{mg} / l. \qquad (5)$$

Instantaneous value of the magnetic flux density $B(t)$ is determined by using voltage signal $u_2(t)$ by

$$B(t) = \frac{1}{N_{ms}S_C}\sum_p \frac{U_{2mp}}{p\omega}\cos(p\omega t + \varphi_p), \qquad (6)$$

Where $\omega = 2\pi f$ is signal of the first harmonic angular frequency, U_{2mp} and φ_p are, correspondingly, voltage $u_2(t)$ of the harmonic components amplitude and of the initial phase obtained from the expansion into a Fourier series.

A possibility to determine the relationships between magnetic losses measured at different frequencies was investigated, the aim of which was to separate them into hysteresis and eddy current losses at a constant magnetic flux. In this case the voltage amplitude must change proportionally to its frequency

$$\frac{U}{f} = const, \qquad (7)$$

Where U, f are the amplitude and frequency of the supply voltage.

The values of hysteresis and eddy current losses components are expressed by relation:

$$P_\mu = P_{\mu h} + P_{\mu ec} = C_h f + C_{ec} f^2, \qquad (8)$$

Where P_μ, $P_{\mu h}$ and $P_{\mu ec}$ are total magnetic losses, hysteresis and eddy current losses, accordingly; C_h and C_{ec} are the corresponding coefficients.

Specific hysteresis and eddy current losses are found from coefficients C_h and C_{ec} in accordance with the relations:

$$p_{\mu h1,0/50} = \frac{50C_h}{m\left(\frac{B_m}{1,0}\right)^2} \tag{9}$$

and

$$p_{\mu ec1,0/50} = \frac{2500C_{ec}}{m\left(\frac{B_m}{1,0}\right)^2}, \tag{10}$$

where $p_{\mu h1,0/50}$ and $p_{\mu ec1,0/50}$ are specific hysteresis and eddy current losses at the values of magnetic induction of 1T and frequency of 50 Hz, B_m is magnetic induction for which coefficients C_h and C_{ec} were found and m is a mass of the tested sample.

Then, by means of solving the equation system

$$\begin{cases} p_{\mu h1,0/50} + p_{\mu ec1,0/50} = p_{\mu 1,0/50} \\ p_{\mu h1,0/50}\left(\frac{f}{50}\right) + p_{\mu ec1,0/50}\left(\frac{f}{50}\right)^2 = p_{\mu 1,0/50}\left(\frac{f}{50}\right)^\alpha \end{cases} \tag{11}$$

when there are two arbitrary similar values of frequency, the values of specific magnetic losses $p_{\mu 1,0/50}$ at magnetic flux density of 1 T, frequency of 50 Hz and at coefficient a are defined. These results are used to define the value of total magnetic losses for the developed SMC structure in the function of magnetic flux density and frequency.

4. Production and analysis of experimental smc samples

In our research, the sample produced from Hoganas (Sweden) soft magnetic powder material Somaloy 700 served as a reference. This material has one of the best electrical and magnetic properties at present.

During the research process it was taken into consideration that all the mentioned properties are achieved when the composite compactness is increased and also when the additives are added to the iron powder to improve the desired properties. It means that powder can be pressed into a high-density composite, which is easily taken out of a press tool and preserves good quality of the surface.

The powder was finished in the form of electrically isolated particles forming soft-magnetic material. Fatty acid amides, colophony and lump rubber were used as electrical insulators. Besides, a phosphorous containing insulating layer was also made.

Many samples of SMC rings, with parameters given in Table 1, were made by various methods. Sample No.1 was made from Hoganes (Sweden) material, sample No. 2 is a laminated structure (magnetically oriented powder) with plastic bonding material based on lump rubber with annealing parameters $T_2 = 1150^0$ C and $t_2 = 0,5$ h, sample No. 3 is an isotropic structure with plastic bonding material based on colophony with annealing parameters $T_3 = 900^0$ C and $t_3 = 2$ h, samples No. 4-5 are made as isotropic structures with plastic bonding material based on lump rubber with annealing parameters $T_4 = 1100^0$ C, $t_4 = 1$ h and $T_5 = 1150^0$ C, $t_5 = 0,5$ h.

Analyzed properties are given in Table 2. Figures 6 – 10 show a family of hysteresis loops for produced samples. The excitation frequency was 50 Hz. Fig. 11 demonstrates the dependence of iron losses in the function of magnetic flux density at this frequency.

Table 1: Parameters of the samples

Param.	Samp. No. 1	Samp. No. 2	Samp. No. 3	Samp. No. 4	Samp. No. 5
Outer diameter /cm	5,5	2	2,14	2,1	2,1
Inner diameter /cm	4,5	1,45	1,5	1,5	01,5
Height /cm	0,98	0,17	0,27	0,33	0,29
Mass /g	60	2	3	3	3
N_{mg}	85	65	65	65	65
N_{ms}	100	60	100	100	100
R_{mg} /Ω	1,6*	0,15	–	0,16	0,17
R_{ms} /Ω	3,5*	1,54	–	3,18	3,05

* Resistance was measured by *U-I* method, in other cases by measuring bridge.

Table 2: Results of magnetic and electrical parameters for analyzed samples

Param.	Samp. No. 1	Samp. No. 2	Samp. No. 3	Samp. No. 4	Samp. No. 5
Residual magnetization /T	0,18	0,39	0,22	0,19	0,18
Coercive force /(A/m)	153	379	668	574	553
Saturation point B/H /(T/A/m)	0,42/756	0,62/795	0,31/1160	0,22/735	0,24/1075
Specific iron losses B_m=0,4T, f=50Hz* /(W/kg)	0,45	0,66	3,74	≈5,5	≈3,8

*For a number of samples there was not possible to determine iron losses at magnetic flux density 1T, because it was physically impossible to reach required level (sample get magnetically saturated before 1T).

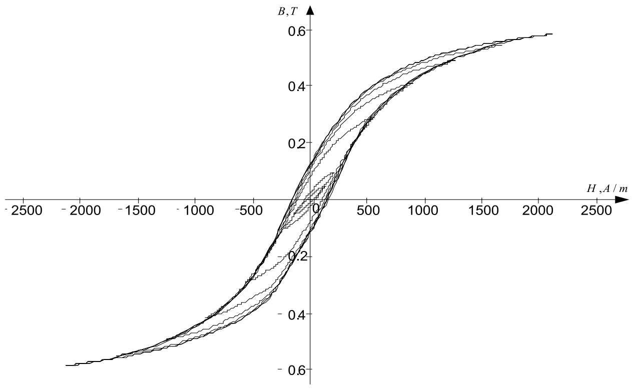

Fig. 6: Family of hysteresis loops for a sample made from Hoganes powder material

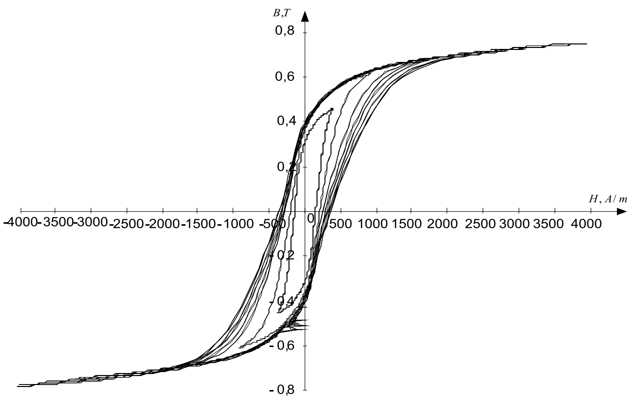

Fig. 7: Hysteresis loops for sample No. 2

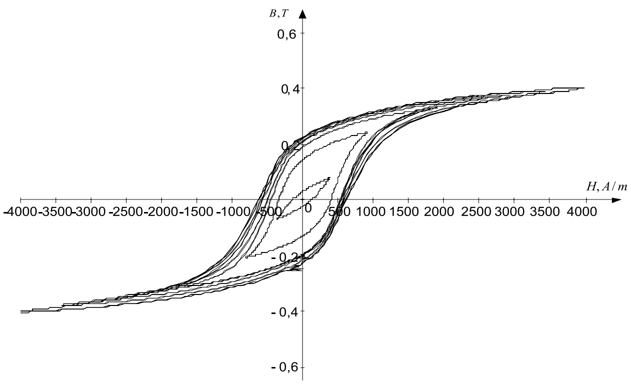

Fig. 8: Hysteresis loops for sample No. 3

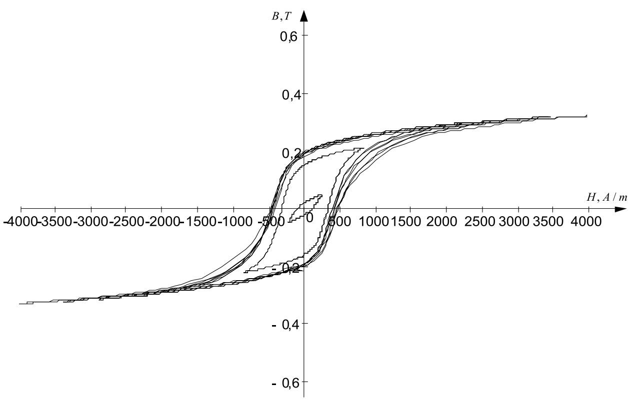

Fig. 9: Hysteresis loops for sample No. 4

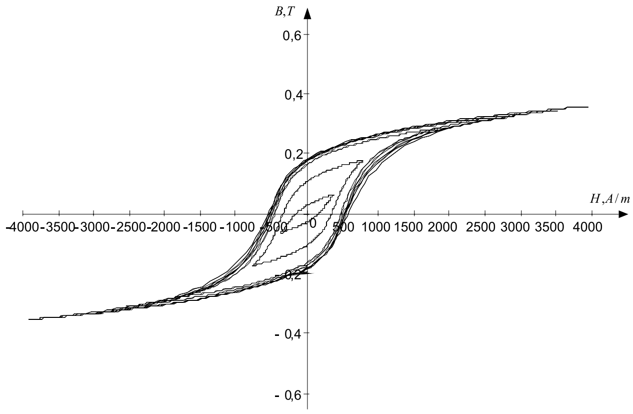

Fig. 10: Hysteresis loops for sample No. 5

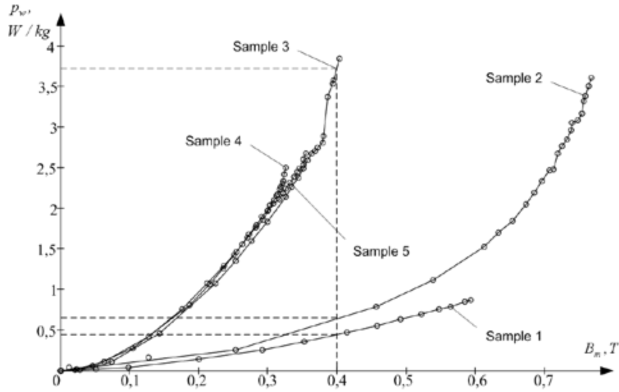

Fig. 11: Iron losses curves pμ = f(B_m) for the analysed samples

The results show that the nearest sample to the one made from the Hoganas company material is the sample No. 2 presenting a laminated powder structure. This structure is very promising for further research related to material structure improvement and to optimization of manufacturing process.

Comparison of the gained results with the known data for the used material show that the error of the parameters measurement is within the permissible limits. Hence, the developed measuring system can be used to determine the properties of soft-magnetic composite materials.

5. Conclusions

The procedure of preparing the mixture of soft-magnetic composite material was presented. The influence of different manufacturing processes in achieving particular structures and properties of SMC material was explained. Different samples were prepared and analyzed during the research. The sample produced from Hoganas ferromagnetic powder material served as a reference from the point of mechanical, electrical and magnetic characteristics. A measuring system was developed, which enables to analyze magnetic properties of developed SMC material. The system allows to measure hysteresis loops and iron losses at different excitation levels and frequencies. The results show that the sample No. 2 presenting a novel laminated powder structure has properties similar to the reference one. Further research will be based on the laminated powder structures as most prospective from the point of view of obtaining the required mechanical, electrical and magnetic characteristics within the focus of material cost reduction.

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