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Original article

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MAGNETICALLY SOFT COMPOSITES BASED ON IRON POWDERS FOR CREATING COMPONENTS OF A TWO-STATOR COMBINED ELECTRIC MOTOR

Abstract. An experimental prototype of electric motor on permanent (FeNdB) magnets with switchable magnetic flux with two sectioned stators and a rotor using SMC material based on encapsulated metal powders has been developed. The method of manufacture of magnetic cores by powder metallurgy method on the basis of magnetically soft encapsulated titanium dioxide composites has been developed, including computer modeling of magnetic cores components, creation of tooling for their manufacture by pressing and selection of technological modes of pressing. Press set for manufacturing stator components by pressing in the form of a mold was made of hardened 5XHB steel. With its use magnetic components for two-stator combined electric motor are pressed. The main electromagnetic characteristics of the components were measured with an express magnetometer. Complex studies showed that the magnetic components have sufficient strength and the necessary electromagnetic characteristics to create a two-stator combined electric motor of this type. An experimental sample of electric motor with maximum power of 15 kW was created on the basis of manufactured magnetic components. Advantages of composite material over electrical steel and other soft magnetic alloys allow providing their wider application in electric machines in order to increase specific power at high speed of rotation with less losses.

Keywords: magnetically soft composites, insulating coatings, electromagnetic losses, magnetic permeability, electric motor

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МАГНИТОМЯГКИЕ КОМПОЗИТЫ НА ОСНОВЕ ПОРОШКОВ ЖЕЛЕЗА ДЛЯ СОЗДАНИЯ КОМПОНЕНТОВ ДВУХСТАТОРНОГО КОМБИНИРОВАННОГО ЭЛЕКТРОДВИГАТЕЛЯ

Аннотация. Разработан экспериментальный образец электродвигателя с переключаемым магнитным потоком с двумя секционированными статорами и ротором на постоянных (FeNdB) магнитах с применением SMC-материала на основе капсулированных металлических порошков. Создана методика изготовления магнитопроводов на основе магнитомягких капсулированных диоксидом титана композитов методом порошковой металлургии, включающая в себя компьютерное моделирование компонентов магнитопроводов, создание оснастки для их изготовления методом прессования и выбор технологических режимов прессования. Оснастка для компонентов статора методом прессования в виде пресс-формы изготовлена из закаленной стали 5ХНВ. С ее применением спрессованы магнитные компоненты для двухстаторного комбинированного электродвигателя. Основные электромагнитные характеристики компонентов измерены с помощью экспресс-магнетометра. Комплексные исследования показали, что магнитные компоненты обладают достаточной прочностью и необходимыми электромагнитными характеристиками для создания двухстаторного комбинированного данного типа электродвигателя. На основе изготовленных магнитных компонентов создан экспериментальный образец электродвигателя с максимальной расчетной мощностью 15 кВт. Преимущества композиционного материала перед электротехнической сталью и другими магнитомягкими сплавами позволяют обеспечить более широкое их применение в электрических машинах с целью повышения удельной мощности при высокой скорости вращения с меньшими потерями.

Ключевые слова: магнитомягкие композиты, изолирующие покрытия, электромагнитные потери, магнитная проницаемость, электродвигатель

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Introduction. In today's environment, electric motors play a very important role for both industrial and domestic applications. With the continuing trend of development of electric transport, more and more requirements are placed on electric motors, such as increased specific power with good heat dissipation, high reliability, cost-effectiveness, etc. [1]. In order to create new types of high-performance electric motors in the world, many scientific teams develop new electromagnetic materials [2]. Over the past years, various types of magnetic materials, such as pure iron-based and its alloys, such as Fe-Ni, Fe-Ni-P, Fe-Nd-B, Fe-Si and Fe-Si-Cr, etc., have been used [3–8]. An information analysis of a large amount of data on the study of technological schemes for obtaining powder magnetically soft materials and the study of the magnetic and physico-mechanical properties of experimental samples shows that one of the promising directions for the further development of such materials is the creation of materials based on nanocrystalline powders [9]. A unique combination of magnetic properties is observed in nanocrystalline alloys based on the Fe-Si-B system of the "Finemet" type ($Fe_{73.5}Si_{13.5}B_9Nb_3Cu_1$) [10] with a mixed amorphous-crystalline structure and a grain size of ~ 10 nm, which makes it possible to obtain saturation induction not less than 1.0 T and high initial magnetic permeability. The absence of a domain structure ensures a low coercive force (5–10 A/m), a correspondingly small area of the hysteresis loop, and, as a consequence, low magnetization reversal losses in such materials [11].

Among many advanced magnetic materials, magnetically soft composite (SMC) seems very promising for the development of new electric motors due to its unique properties such as magnetic and thermal isotropy, very low eddy current losses and the prospect of inexpensive mass production [12–14]. SMC can be described as particles of ferromagnetic powder surrounded by an electrically insulating coating [9]. SMC components are typically manufactured by powder metallurgy methods in combination with new technologies such as two-step pressing, hot pressing, multi-stage and magnetic annealing followed by heat treatment at relatively low temperatures. Using proven powder metallurgy methods, SMC components can be pressed to the desired shape and size in the mold, so no further processing is required and production costs can be significantly reduced [15, 16].

These composites have a number of advantages over traditional multi-layer cores based on electrical steel. They have unique properties that include: three-dimensional (3D) isotropic ferromagnetic behavior, very low eddy current losses, relatively low total core losses at medium and high frequencies, opportunities to improve thermal performance, simplified motor design and assembly, and prospects for significantly reduced weight and manufacturing costs. With such composites it is possible to reduce the weight and size of electrical engine components. Magnetic isotropy and negligible eddy current losses offer great design advantages as the limitations of electrical steel are removed. Radically different configurations can be used to make full use of space, resulting in a very high power density or power-to-volume ratio [17, 18].

The laminated sheet metal core has a much lower thermal conductivity in the direction perpendicular to the lamination plane than the thermal conductivity inside the laminated sheet, so the heat in laminated cores is almost completely transferred to the lamination edge. SMC cores dissipate heat in all directions, which provides high flexibility in thermal design [19]. In addition, most attractive advantage of SMC may be its environmental friendliness. Material waste in production is kept to a minimum. In addition, used SMC-based motors can easily be shredded to separate and reuse valuable materials such as copper, providing much better recyclability than laminated steel-based motors.

Worldwide industry standards determine magnetic properties only for individual sheets of electrical steel [20]. However, measurements are made for an individual sheet before it is laid, and it is known that there are discrepancies between calculated values and actual measurements of motor performance [21]. This is because the magnetic properties are degraded due to deformation caused by stress and thermal deformation that occurs during stamping, caulking and welding. On the other hand, the SMC magnetic properties are measured on a sample created using the same compacting method as the final product. Thus, the gaps between the design values and the actual motor performance measurements are small. In addition, the SMC has excellent high-frequency characteristics. So, the SMC used in the motor can suppress the high-frequency noise generated by the inverter [22–25].

The most common approach to increasing the torque of power systems is to use electric motors with an external rotor and mechanical gears. However, the use of a mechanical gear leads to a decrease in drive power and creates additional problems with lubrication, cooling and maintenance of the mechanical gear [26]. It is more convenient to use a combination of two stators and one rotor in one electric motor with double air gap [27–29]. This motor has a variety of applications, with higher power and torque. The use of two stators further increases reliability, in addition, two stators can potentially reduce torque ripple. Synchronous motors are widely used because of their high efficiency and ease of control, and they have the advantages of simple design and control.

This paper focuses on the development of a switchable magnetic flux motor with two sectioned stators and a rotor on permanent (NdFeB) magnets using SMC material based on encapsulated metal powders.

Experimental results. As the base of the obtained magnetically soft composite, the extra pure Swedish water-atomized iron powder ABC100.30 was chosen. An insulating layer was deposited on the surface of the powder particles using a combined technique [30]. The thickness of the coatings depended on the deposition time on the powder particles and the concentration of the alcoholic acid solution. The advantage of the above technique of oxide coatings obtaining by decomposition of metal sulfates and nitrides is its relative simplicity and low cost [31].

Measurement of composites electromagnetic characteristics was carried out in a wide range of magnetic fields change at a frequency of 1 kHz using an express magnetometer developed and manufactured in the laboratory of physics of magnetic materials. From the field dependencies of magnetization obtained with the express magnetometer (Figure 1), the value of electromagnetic losses and the value of induction were calculated. In our case, eddy currents are practically absent due to the insulating of each powder particle by titanium dioxide oxide layer. Thus, with increasing magnetic induction the value of electromagnetic losses increases almost linearly (Figure 2) due to hysteresis losses in the entire measurement range. For induction B = 1.9 T the hysteresis losses in composites are P = 105 W/kg which is lower than similar losses of electrical steel P = 120 W/kg. It can be concluded from the data analysis that the developed composite magnetically soft materials have a high value of magnetic induction of 1.88 T in the field of 21 kA/m.

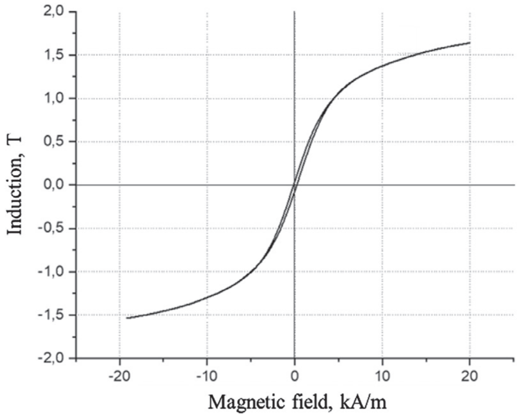


Figure 1. Magnetization loops at 1 kHz of titanium oxide-encapsulated composite

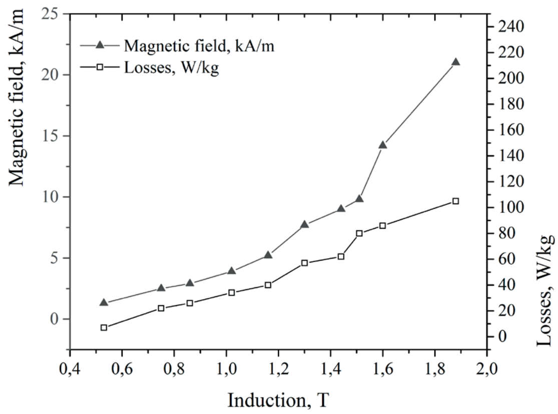


Figure 2. Magnetization dependences measured at 1 kHz and field dependencies of hysteresis losses for a composite based on iron powder encapsulated with titanium oxide coating

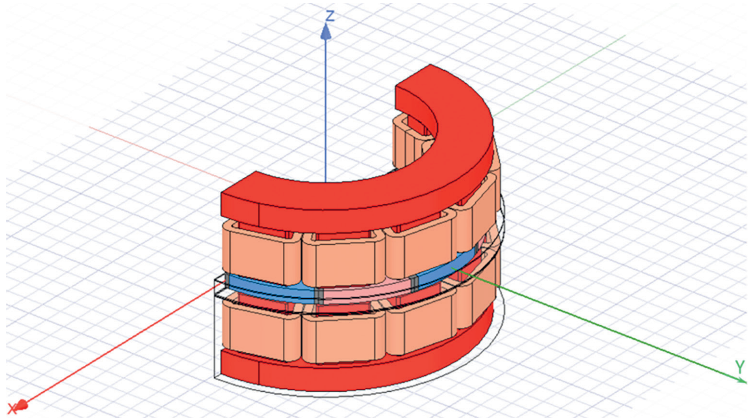


Figure 3. A view of the calculation model of the axial airflow motor: red corresponds to the powder SMC material, blue and pink to magnets, black to the non-magnetic non-conductive rotor carcass, and orange to copper

Advantages of composite magnetic material over electrical steel and other soft magnetic alloys allow providing their wider application in electric machines in order to increase specific power at high rotational speed with less losses. Significant increase in the efficiency of electric machines (electric motors, generators, etc.) is possible by changing the design solutions, for example, creation of so-called double-stator axial electric motor-generator. Such a solution involves changing the direction of magnetic flux in the magnetic core. On the basis of traditional materials, such as electrical steel, it is impossible to implement such a solution. Developed new composite material allows making cores on its basis, which allow changing the direction of magnetic field.

Technique of magnetic cores manufacturing includes computer modeling of magnetic cores components, creation of tooling for their manufacturing by pressing method and selection of technological modes of pressing. At the first stage, taking into account electromagnetic parameters of composites, simulation of synchronous motor with excitation from permanent magnets of axial magnetic flux with double stator and magnetic core made of magnetically soft composite material is performed. Figure 3 shows the appearance of the model of the magnetic circuit of the motor under study. In order to reduce the simulation time it is preferable to calculate the model reduced by 2 times, containing 6 magnets on the rotor and 7 teeth on each stator with setting of appropriate boundary conditions. In Table are presented the calculated electrical parameters of the two-stator motor.

The calculations show that the average torque value is 48.4 N·m, which translates to a power output of 15.340 W. This mode of operation is short-lived due to the high current density (14.77 A/mm^2, see Table). Long-term operation while maintaining maximum power is possible only with water cooling. Normal conditions and typical values of current density for long-term operation are 8–10 A/mm^2 with a proportional power reduction to 10 kW.

Electrical parameters of the motor

Parameter	Value
Power supply voltage, V	24–72
Maximum phase current (pc), A	210
Current density (RMS), A/mm^2	14.77
Rotation speed, min^{-1}	5000
Maximum capacity, kW	15
Nominal capacity, kW	10

The amplitude of torque pulsations is less than 2 H·m, which is less than 5 % of the average torque developed by the motor, which is a low value and means little noise and no vibration during motor operation. The small torque pulsation is a consequence of the inherent advantage of the chosen ratio of stator teeth z to the number of rotor magnets $2p$: $z = 2p \pm 2$. The losses in the stator magnetic core have an average steady-state value of about 170 W and are the least significant among all losses. The main component of losses in stator magnetic core is remagnetization losses of hysteresis loop, which were about 150 W, losses on eddy currents are insignificant, their value was 20 W.

At the second stage, taking into account computer modeling, tooling for manufacturing stator components by pressing method was created. The tooling is a mold consisting of an inner part and a supporting mandrel made of 5XHB steel hardened to Rockwell hardness of 55–60 and 45–50 HRC, respectively.

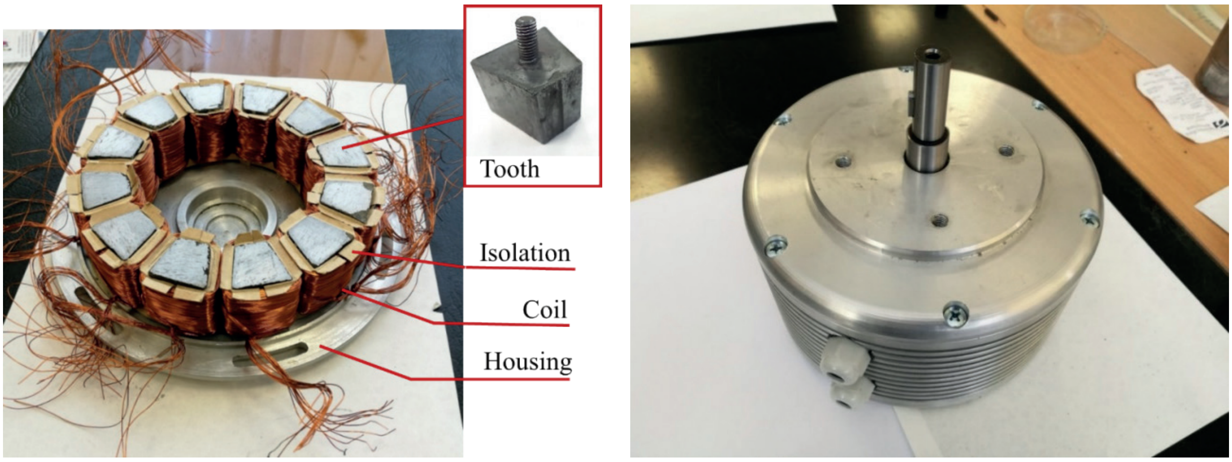
Further, the choice of technological modes of pressing the magnetic components was made. The operation of pressing magnetic components includes lubrication of encapsulated iron powder with addition of peat wax solution (Peat wax), direct manufacturing of stator components by hydrostatic pressing of encapsulated iron powder in a mold under pressure 8–10 t/cm^2 under normal conditions and heat treatment of manufactured components to normalize their physical parameters. The components are annealed at a temperature of 400 °C during 1 hour in special autoclaves. Under such technological regimes the density of the pressed composite is of the order of 7.5–7.8 g/cm^3.

To create the stator of an electric motor, 12 teeth were made, a photo of one of them is shown in Figure 4, *a* (insert).

The strength characteristics of magnetic components are evaluated using Brinell hardness measurements. This method is important when evaluating the mechanical properties of products and their components during operation, during the current state control of structures and during emergency investigations. It is especially important for detecting and estimating the condition of locally deformed zones of structures, which have an increased hardness as compared to the hardness of the original material. Such zones are the sources of initiation and development of cracks. Magnetic components of the developed composites have HB hardness values from 83.16 to 101.86, which is higher than the hardness value for pure iron HB60. This indicates that the products have an increased tensile strength, and the absence of cracks indicates that the material is highly resistant to the occurrence and development of cracks. Studies have shown that the magnetic components have sufficient strength and the necessary electromagnetic characteristics to create a two-stator combined motor.

Experimental sample of two-stator electric motor is made using prepared two stators with winded coils (Figure 4, *a*) and rotor. Calculation of the stator winding data and the main parameters of the power supply was performed for operation with induction at maximum of the order of 1.5 T and the motor power supply directly. To achieve the value of magnetic induction in the pulse equal to 1.5 T the value of magnetic field strength is of the order of 7–8 kA/m. According to these conditions and the possibility of the power supply the number of turns of the stator winding is determined. The electric motor housing is made of duralumin disks with holes for fixing screws (Figure 4, *b*). Diameter of discs was 15 cm. Before assembly, fourteen NdFeB magnets with the following parameters were glued on the rotor made on the basis of the developed soft magnetic material: residual induction 1.15 T, coercive force of magnetization 850 kA/m, magnetic permeability 1.05. The shaft of the two-stator motor is made of stainless steel.

The obtained scientific results indicate the possibility of creating components for various electrical devices on the basis of new magnetically soft composite materials. The possibility of application of stator and rotor made of powder composite magnetically soft material for manufacturing of two-stator electric motor has been investigated. Such requirements are satisfied by composite materials based on metal



a *b*

Figure 4. Winding motor stator (*a*), and the assembled electric motor (*b*)

powders, the particles of which are covered with a very thin layer with electrical insulation. Application of insulating layers provides reduction of electromagnetic losses and increases the quality factor of composites.

The developed method allows creation of magnetic cores for electric motors from soft magnetic composite materials by the powder metallurgy method. The advantages of composite magnetic material over electrical steel and other soft magnetic alloys allow providing their wider application in electric machines in order to increase the specific power at high rotation speed with less losses.

Conclusions. Magnetic components for a two-stator combined electric motor were produced by the powder metallurgy method on the basis of magnetically soft encapsulated titanium dioxide composites. The density of the manufactured components is 7.5–7.8 g/cm^3. Measurements of the main electromagnetic characteristics of the magnetic components were made on an express magnetometer at a frequency of 1 kHz. At intensity H = 21 kA/m the value of magnetic induction of magnetic components is B_m = 1.88 T. The value of hysteresis losses of components is on the order of P = 105 W/kg for the induction value B = 1.9 T, which is lower than the value of similar losses for electrical steel P = 120 W/kg. Complex studies have shown that the magnetic components have sufficient strength and the necessary electromagnetic characteristics to create a two-stator combined electric motor with a rated power of about 10 kW. Calculation of stator winding data and basic parameters of power supply unit was made for operation with induction at maximum of about 1.5 T and power supply of the motor directly. Experimental sample of two-stator electric motor is assembled from prepared two stators with winded coils and rotor.

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