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Properties of a composite magnetically soft material based on coated iron powders

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Abstract. A method has been developed to study the properties of composite SMC materials based on high-purity iron powders, the lowest carbon content materials, for example, ABC100.30 iron powder, have higher values of magnetic parameters and minimal losses. The structure and morphology of the surface of the obtained composite materials were studied. The results of the influence on the properties of SMC materials of various insulating coatings were obtained, and SMC materials with titanium oxide coatings had better characteristics. The influence of the thickness of the oxide coating on the decrease in magnetic permeability of SMC materials was studied. The influence of insulating coatings' thickness on the SMC material's magnetic properties was determined.

1 Introduction

The use and production of automobiles are expanding rapidly, in line with the growing population of Uzbekistan. The increased number of cars hurts the environment, and the lack of component resources complicates the situation [1-3]. One of the urgent problems is the lack of resources, and it is important to create resource-saving technologies and methods.

Consequently, developing electric vehicles as an alternative to internal combustion engines is one of the most reasonable ways. Electric vehicles do not emit harmful substances into the environment and are also easy to operate [1, 2].

World manufacturers, one after another, announce their intention to make producing electric vehicles their main goal. Some hope that battery-powered cars will form part of the company's sales, while others intend to reject completely internal combustion engines (ICEs), both diesel and gasoline.

And this is logical since the mass transition to electric transport is explained by manufacturers primarily by concern for the environment.

In terms of the development of electric vehicles, Uzbekistan follows global trends. In particular, under the Uzbek-Belarusian project, work is underway to develop new magnetic materials and methods for manufacturing magnetic circuits based on them for building prototypes of mini-electric transport [1,2].

Introducing our ecological mini-electric vehicle will allow the use of intensive methods in the field of production, primarily modern energy-saving technologies in parks and

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entertainment areas, in a priority direction. To achieve these indicators, it is important to improve technologies and create new technical means and efficient use [1, 2, 4].

In recent years, many centers have been intensively researching soft magnetic composite materials (SMC) based on the use of soft magnetic particles, usually based on iron, with an electrically insulating coating on each particle [5-9]. The main purpose of the low-frequency composite soft magnetic material is the construction with its use of highly efficient inverter-driven valve motors, transformers, chokes, and other devices for which the operating frequency of magnetization reversal significantly exceeds the industrial frequency [10-12].

Somaloy powders (Hoganas company) are offered as a commercial composite soft magnetic material [13, 14]. However, individual parameters of such materials, primarily losses due to magnetization reversal and their high cost, do not quite suit consumers.

The properties of composite magnetic materials depend and are determined by several factors. The basis of the composite magnetic material is also important - especially pure iron powder - its chemical composition, fractional composition, surface adhesion of particles, and some other factors [15-17].

Therefore, the work aims to study the properties of a low-frequency magnetically soft material with the optimal choice of an insulating coating and directly the type of high-purity iron powder.

Because of this, to achieve the work goal, develop an electric motor for mini electric transport based on a composite magnetically soft material. At the same time, the task was set to study a composite magnetically soft material based on iron powders with coatings and to develop a method for studying the properties of composite SMC materials based on high-purity iron powders. The result is a composite magnetically soft material based on iron powders with coatings for an electric motor.

2 Materials and Methods

The technology for manufacturing isolated powders of magnetically soft materials and manufacturing products from them is a multi-stage process that includes the following main operations:

– an operation for the reaction deposition of insulating coatings from the gas phase at a temperature of 150–200°C [18]. In this work, we studied composite materials based on high-purity iron powders ASC100.29, ABC100.30, and Atomet 1001HP, on the surface of which insulating coatings were applied using various oxide solutions and suspensions. The chemical composition of the studied iron powders is given in Table 1.

- an operation to fix coatings by applying a small amount of silicone varnish solution and lubricant.

- an operation to manufacture products by hydrostatic pressing isolated powders in special molds. The pressed products were subjected to heat treatment to normalize the physical parameters. Samples are annealed at a temperature of 400–600°C in a vacuum or air.

TABLE 1. Chemical composition, wt.%

	C	O
ASC100.29	0.01	0.08
Atomed 1001HP	0.004	0.06
ABC100.30	0.002	0.05

To study the magnetic properties, samples of composite magnetic material in the form of rings with dimensions of 24 × 13 × 8 mm were fabricated by powder metallurgy by

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pressing the prepared, isolated powder and then subjected to annealing. The density of the finished products was in the range of 7.6 to 7.75 g/cm^3.

Measurements of the magnetic properties were carried out both on an express magnetometer, where losses and other magnetic parameters were determined from the magnetization reversal curves of the samples, and additionally by a direct method by measuring the heating rate of the core during operation in the adiabatic mode. Both of these methods showed good agreement between the measurement results.

The high resistivity of the composite SMC material of the order of ρ= 10-2 –10-1 Ohm·m determines the almost absence of eddy current losses.

Hysteresis losses in the express magnetometer are determined based on the expression:

$$W = w_S f \frac{V}{2m}, \text{Wt/kg} \quad (1)$$

w_s is the area of a single magnetization reversal cycle (J), V is the volume of the sample (m^3), m is the mass of the sample (kg), f is the frequency. In this case, the maximum values of the field strength and the maximum induction on the magnetization curves were simultaneously recorded.

The process of heating the core during its operation in an electrical circuit at the initial stage near room temperature can be considered adiabatic, with practically no heat removal. In this case, the specific losses for the remagnetization of the core are determined [14, 19]:

$$W = q\Delta T / \Delta t, \text{Wt/kg} \quad (2)$$

where q is the specific heat capacity of the composite material, ΔT/Δt is the core heating rate.

3 Results and Discussion

To obtain various composite materials, primarily magnetization reversal losses, the solutions, and suspensions shown in Table 2 were used. Losses were measured both on an express magnetometer and by a direct method by measuring the heating rate of the core during operation in the adiabatic mode. The above table shows that the magnetization reversal losses for all used coatings, except titanium oxide, are practically the same, regardless of their properties.

In this regard, the iron powder's initial properties are decisive in forming the properties of composite magnetic materials [20-22]. Figure 1 shows the results of studying the dependence of magnetization reversal losses on the magnitude of magnetic induction at a frequency of 1 kHz for composite materials based on iron powders ASC100.29, ABC100.30, and Atomet 1001HP.

As seen from Fig. 1, the losses are maximum for composite materials based on ASC100.29 and minimal for materials based on ABC100.30. It can be assumed that the carbon content in the initial iron powders affects the magnetization reversal losses (Table 1). Figure 2 shows the dependence of the magnetization reversal loss on the carbon content in the initial iron powders.

The above table shows that the magnetization reversal losses for all used coatings, except titanium oxide, are practically the same, regardless of their properties.

Figure 3 shows the comparative curves of the field dependences of the magnetic induction in the commercial material Somaloy - 1, the composite material on iron powder ABC100.30 when titanium oxide - 2 is used as an insulating coating and electrical steel

3412, with a tape thickness of 0.35 mm - 3. It can be seen from the figure that the permeability in SMC material based on ABC100.30 is somewhat higher. The manufacturing technology of both samples was identical.

TABLE 2. Losses in material based on ASC100.29 with additives of the same volume at a frequency of 1 kHz

Type of insulating coating	Induction, T	Losses, Wt/kg
P_2O_5	1.54	110
$P_2O_5 + B_2O_3$	1.52	115
CrO_3	1.55	110
BN	1.58	120
B_2O_3	1.54	120
CHOH	1.50	150
SiO_2	1.50	120
TiO_2	1.50	65

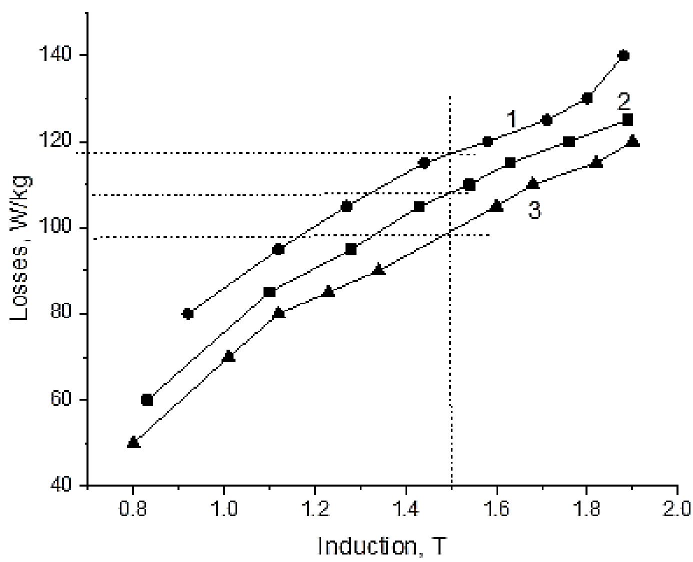

Fig. 1. Dependence of losses on magnetic induction for composite materials based on powders ASC100.29 - 1, 1001HP - 2, ABC100.30 - 3. at a frequency of 1 kHz and the same thickness of the insulating layer based on boron oxide

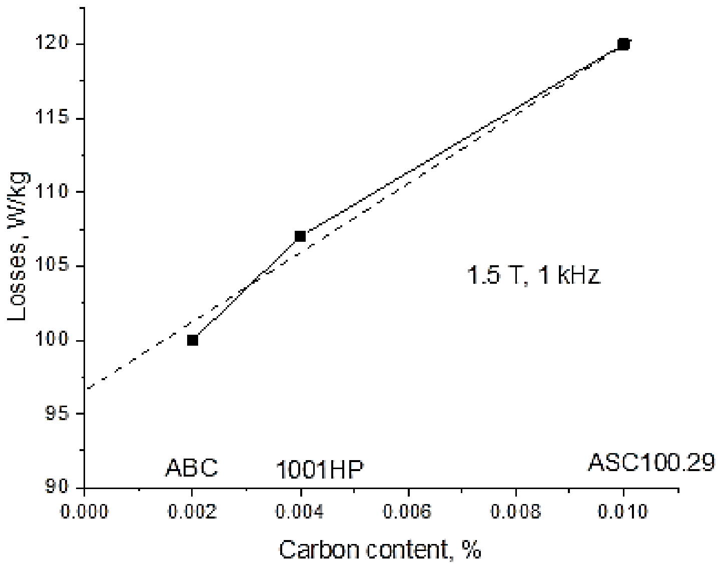

Fig. 2. Dependence of SMC losses based on iron powders ABC100.30, Atomet1001HP, and ASC100.29 at a frequency of 1 kHz and an induction of 1.5 T on the carbon content

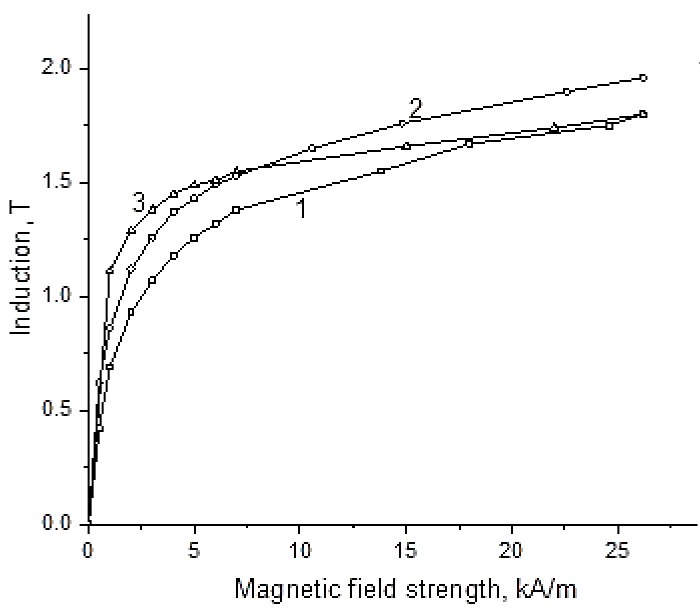

Fig. 3. Magnetization curves of Somaloy - 1, SMC based on ABC100.30 powder with TiO_2 insulation - 2, Electrical steel 3412 (E320) - 3. Somaloy - density after firing ρ = 7.5 g/cm^3. SMC – density ρ= 7.7 g/cm^3

The dependence of losses on remagnetization on the value of magnetic induction at a frequency of 1 kHz in Somaloy -1, a composite material on iron powder ABC100.30 when using titanium oxide - 2 as an insulating coating and electrical steel 3412 - 3 are shown in

Fig.4. It can be seen from Fig. 4 that the losses are minimal in the SMC material based on ABC100.30 powder. In this case, the field dependence of losses is close to linear.

The results of testing the mechanical properties are summarized in table 3, which shows the data on the tensile strength compared to steels. Samples were made with a diameter of 10 mm and a height of 10 mm, and after their heat treatment, the tensile strength was determined. It can be seen from the table that the maximum tensile strength is typical for a composite material with titanium oxide insulation. The minimum value is typical for material with insulation based on boron nitride. In the latter case, the adhesion of the insulating coating to iron particles is minimal.

TABLE 3. Tensile strength σv for a composite material with various insulating coatings, pressing pressure 7.5 t/cm^2 annealing 400°C/1 hour

Coating type	σv, MPa	Analog
Phosphide coating	380	Ст.1
Oxide titanium coating	510	Ст.5
Boron Oxide coating	320	Ст.0
Coating BN	270	Ст.0

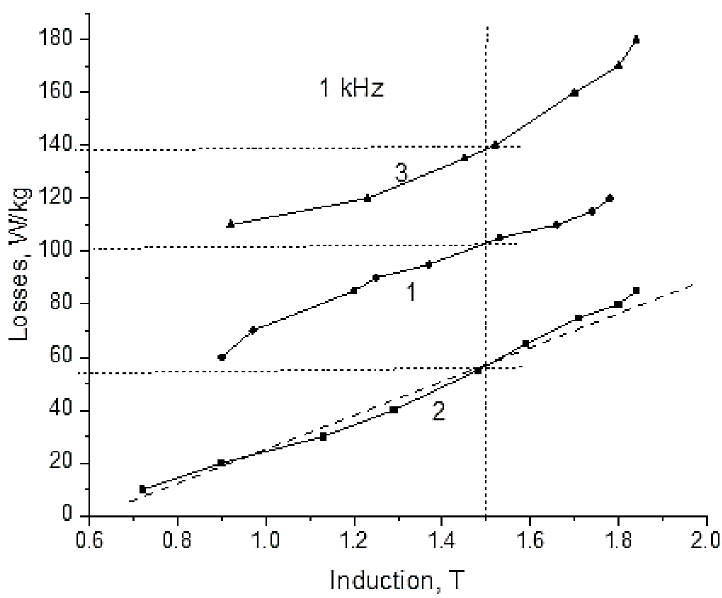

Fig. 4. Losses depending on induction at a frequency of 1 kHz in Somaloy - 1 (or our previous products), SMC based on ABC100.30 powder with TiO_2 insulation - 2, electrical steel sheet 0.35 mm 3412 (E320) - 3

On the base of capsulated by oxide coating water-atomized iron powder ASC100.29, new composite soft magnetic materials were synthesized to replace electrical steel in devices. It was found that the synthesized composite materials have low electromagnetic losses, high values of magnetic induction (up to 2.1 T), and good corrosion resistance. Using such materials in power supplies, chokes, transformers, stators, and rotors of electric machines and other products ensures their stable operation under various conditions [23].

Unlike magnetodielectric, where each metal particle is completely isolated, and conduction between particles is excluded, for a composite magnetically soft material, adjacent metal particles are connected by conduction channels to form a common

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conduction band. In this case, the isolation of metal particles is local, allowing the mutual exchange of conduction electrons. As a result of the mutual flow of electrons, a conduction band is formed, in which the population density of the Fermi surface is determined by the degree of overlap of metal particles. The value of the degree of particle overlap, depending on the thickness of the insulating coating, can vary from zero, typical for magnetodielectric, to the maximum value, typical for metal. In this case, the population of the Fermi level changes from the minimum value for the magnetodielectric $E_f = E_{f1}$ to the maximum value for the metal $E_f = E_{f2}$.

Based on the theory of direct exchange interaction, the electron densities on the Fermi surface for both the metallic state and composite materials should be close. In this case, the magnetic properties of the metallic ferromagnet and the composite material must be identical. This condition can be met in the case of composite magnetic materials if the grain insulation is local and has the minimum possible thickness. As shown by the present studies, the calculated thickness of the insulating layer should be nanometer-sized.

The presented results on the dependence of losses on the carbon content can be considered from the following standpoints. Carbon in the initial powders forms iron carbides, which are the centers of deceleration of domain walls during the remagnetization of the composite material. As a consequence, with an increase in carbon content, the value of the coercive force increases, and, as a result, magnetization reversal losses increase. When using iron powder with zero carbon content, the calculated loss reduction compared to their values for SMC based on ABC100.30 should not exceed 5%.

As for the mechanical properties, the strength of the composite material, in this case, the adhesion of the insulating layer to the metal, plays a decisive role. Studies have shown that the maximum strength is achieved using an insulating layer based on titanium oxide; the minimum strength is typical for insulation based on hexagonal boron nitride.

The conducted studies have shown that further progress in improving the magnetic properties of composite materials and achieving minimum loss values is associated with an improvement in the properties of the iron powder itself. The decrease in the defectiveness of grains of iron powder, determined by the carbon content, which forms iron carbides, is one of the factors in the growth of the coercive force and the reduction of magnetization reversal losses.

4 Conclusion

As a result of the research on optimizing the properties of low-frequency SMC material, the use of ultra-pure iron powders with a minimum carbon content as the basis has minimal losses. When using titanium oxide as an insulating coating, minimum losses and maximum strength values in SMC material are achieved.

Using titanium oxide insulating coatings can significantly reduce magnetization reversal losses compared with commercial SMC material and electrical steels. Due to the almost zero eddy current losses for the materials developed by SMC, one can consider their application for the construction of high-frequency and high-speed electric motors and other products. Thereupon, the influence of the thickness of insulating coatings on the magnetic properties of the SMC material is determined.

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