Magnetic Composites in Electric Motors

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Abstract Magnetic composites are manufactured as magnetic powder bonded by dielectric material, which bond and insulate powder grains. Magnetic composites are applied in electric machines due to their favorable magnetic and mechanical properties as well as possibility of tailoring their physical properties. The paper is a review of soft and hard magnetic composites, their internal structure, properties, and advantages resulted from their application on magnetic circuits of electric motors.

Keywords Magnetic composites · Magnetic and mechanical properties · Electric motors

1 Introduction

Electric motors are devices with relatively high conversion efficiency of electrical energy into mechanical. Further increase of electric motors efficiency could be obtained by an appropriate selection of materials for magnetic circuits, what results

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in a reduction of power losses. In previous paper [1], the impact of the application of modern soft magnetic materials, such as 6.5% Si–Fe steels or amorphous alloys, on power losses generated in electric motors has been analyzed. The anisotropy of magnetic properties, which determines usefulness of the material for construction of magnetic circuits in electric motors, was also discussed. However, it should be noted that despite the favorable magnetic properties of analyzed materials, these have a complicated and expensive production technology.

Designers of electric motors are still looking for new materials that allow them to design electric devices with new structures of magnetic circuits. Such types of materials are magnetic composites, which are produced by bonding magnetic powder by a dielectric material. Magnetic composites have a lot of advantages such as good magnetic and mechanical properties, high resistivity as well as abilities: to tailor physical properties of composites, to produce elements with complicated shapes with high dimensional accuracy, to produce isotropic magnetic circuits with three-dimensional distribution of magnetic flux, to magnetize isotropic permanent magnets in all direction and multipolarly, to produce hybrid elements (i.e., elements with at least two areas having different physical properties), to mechanical forming in the case of prototyping devices and finally—easy recycling and small powder waste.

The use of magnetic composites allows often reducing the volume of magnetic circuits of electric machines, their appropriate shaping and it improves the efficiency of electric units working at a frequency above 300 Hz.

The present paper is focused on production technology of soft and hard magnetic composites, their chosen magnetic and mechanical properties as well as advantages resulted from their application in new construction of electric motors.

2 Technology Production of Magnetic Composites

The main component of magnetic composites is magnetic powder that could be obtained by mechanical or physicochemical methods, such as, e.g., milling of magnetic alloys or by atomization of materials from liquid phase [2–4]. Soft magnetic powders are generally produced by atomization of liquid metal or its alloy. Hard magnetic powders are usually produced by the ingot crushing method, mechanical synthesis or hydrogenation methods. In the case of Nd–Fe–B powders, the most commonly used method is based on the milling of magnetic ribbons obtained by rapid solidification of melt alloy (Melt spun ribbon).

Magnetic powder grains could be coated with a binder during the powder preparing process or alternatively—a mixture of magnetic powder, a binder, and a lubricant are prepared. Binders are used in the preparing of magnetic composites in order to bond powder grains. Binders are dielectrics and create an insulating layer on a surface of powder grains. Photographs of metallographic structures of magnetic composites are depicted in Fig. 1.

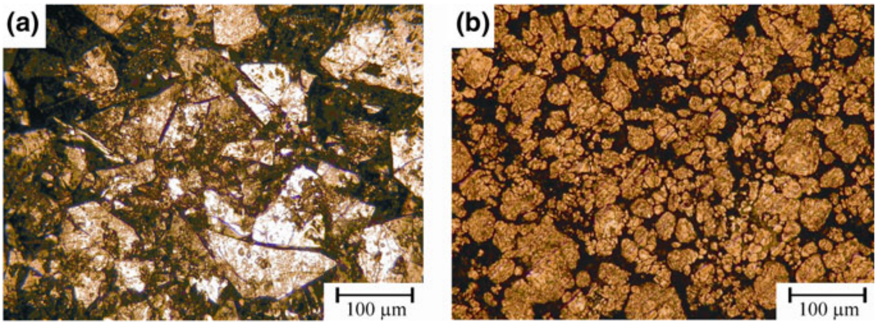


Fig. 1 Metallographic structure of Nd–Fe–B hard magnetic composite (**a**) and iron powder based soft magnetic composite (**b**), zoom 100× [19]

3 Physical Properties of Magnetic Composites

Magnetic, electrical, and mechanical properties of magnetic composites depend on many factors, of which the most important are magnetic properties of powder, size of powder grains, amount, and type of the binder and admixtures, manufacturing technology, and parameters of process (pressure and temperature) [4–21].

Referring to magnetic properties of the powder, two main types of composites can be specified: soft magnetic composites or dielectromagnetics (manufactured from powders of pure iron, soft ferrites and Fe–P, Fe–Si and Fe–Ni alloys) and hard magnetic composites, known as bonded magnets or dielectromagnets (manufactured from powders of Ba- and Sr-based ferrites, Al–Ni–Co, Sm–Co alloys or nanocrystalline Nd–Fe–B alloys) [2, 5, 6, 9, 22, 23].

3.1 Soft Magnetic Composites

Soft magnetic composites are usually manufactured by pressing grains of soft magnetic powder and dielectric binder [6, 19, 23]. The magnetic parameters of soft magnetic composites made of Somaloy 500 powder are shown in Fig. 2 as an example.

A dielectric binder is used in magnetic composites for bonding powder grains and for creating an insulating layer on their surfaces. Powder grains are insulated from each other, what affects significantly physical properties of the material. Dielectric layers are responsible for an increase in resistivity of the magnetic composite and—due to a limitation of eddy current flows—for power losses reduction, especially at higher frequencies. An increase of a dielectric content in the composite makes its magnetic properties worse (lower saturation induction and maximum magnetic permeability), but at the same time, it improves its mechanical properties [3, 6, 11–14, 17, 18, 23–25]. The influence of dielectric volume content

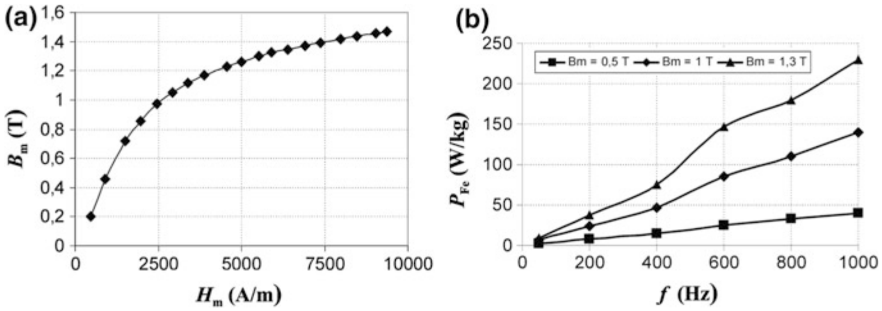


Fig. 2 Magnetic properties of the Somaloy 500 + 0.5% Kenolube composite: magnetization curve at 50 Hz (**a**), frequency dependence of losses at different values of induction (**b**) [19]

Table 1 Chosen magnetic properties of the Silame-type composite [3]

Magnetic parameter	Volume content of dielectric				
	14 vol.%	17 vol.%	20 vol.%	25 vol.%	33 vol.%
B_S (T)	0.72	0.60	0.54	0.51	0.50
μ_{max} (–)	34.7	30.8	33.4	24.3	16.1

on chosen magnetic properties of composite from Silame to nanocrystalline iron-based alloy powder is presented in Table 1.

Physical properties of magnetic composites also depend on the technological parameters, associated with the preparation of magnetic powder (size of grains) as well as the element forming (e.g., pressure and curing temperature) [3, 18–20, 25]. The grains size has a significant impact on the density of compacts. Fine powders have a high internal friction coefficient, which causes losses of the compression pressure and the lower density of a compact. In the case of larger grains, the number of air gaps is lower. Thus, the best physical properties of composites are obtained for magnetic powder with relatively high distribution of grain size.

The properties of magnetic composites manufactured in the pressing process strongly depend on the compacting pressure. The higher compacting pressure causes the lower number and volume of air gaps, what improves magnetic and mechanical properties of the composite. Physical properties of composites also depend on the curing temperature, which is determined by the type of binding materials. If the curing temperature is too high, the insulating layers of grains can be damaged, what causes higher power losses [6, 11–16, 19, 24, 25]. Exemplary influences of the technological parameters on magnetic and mechanical properties of the soft magnetic composite made of the Somaloy 500 powder + 0.6% LB1 are depicted in Figs. 3 and 4.

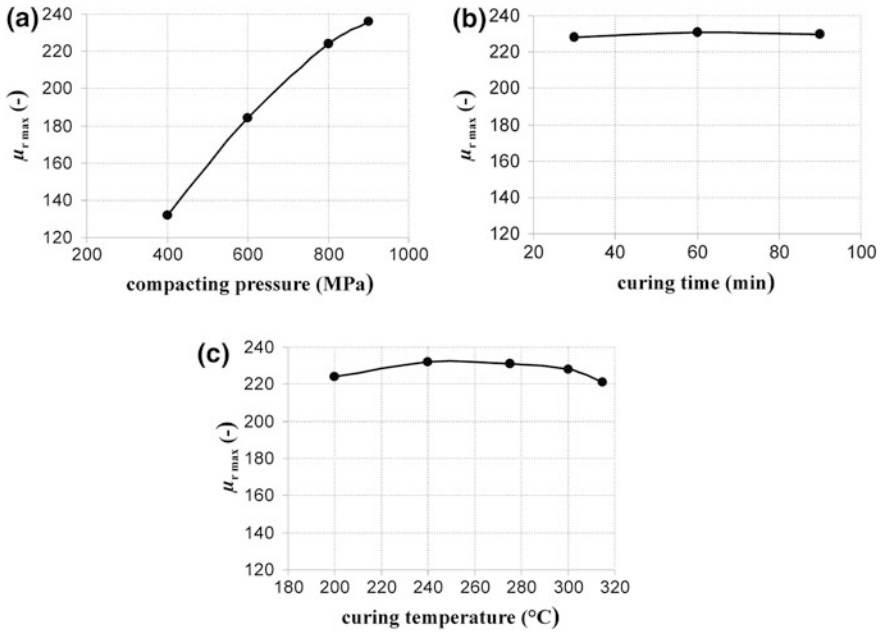


Fig. 3 The influence of technological parameters on maximum magnetic permeability for the soft magnetic composite made of the Somaloy 500 powder + 0.6% LB1: as a function of the compacting pressure (**a**), as a function of the curing time (**b**) and as a function of the curing temperature at 50 Hz (**c**) [19]

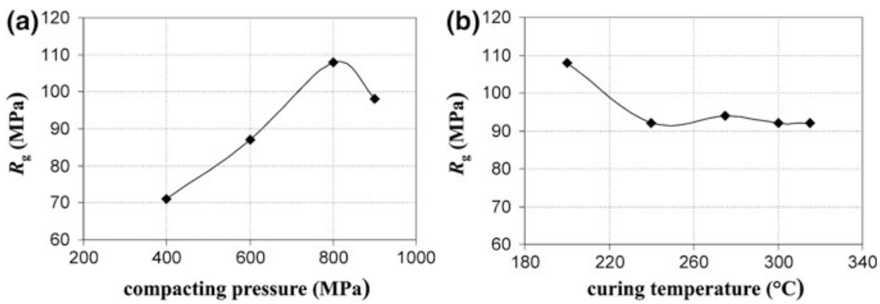


Fig. 4 The influence of the compacting pressure (**a**) and the curing temperature (**b**) on the bending strength for the soft magnetic composite made of the Somaloy 500 powder + 0.6% LB1 [19]

3.2 Hard Magnetic Composites

Hard magnetic composites (bonded magnets, dielectromagnets) are obtained by bonding of hard magnetic powder with dielectric, for example with epoxy resin or a polyamide. The final products are mostly manufactured in the pressing or the injection moulding technologies. As in the case of soft magnetic composites, parameters of the technological process have significant influence on physical properties of bonded magnets. The properties of bonded magnets can be also tailored by appropriate doping of their composition with different types of magnetic and/or nonmagnetic powders as well as by changing the manufacturing parameters [2, 5, 9, 20–22, 26–28].

The bonded magnets are mainly manufactured from powdered Nd–Fe–B nanocrystalline ribbons. The Nd–Fe–B composites have for some applications insufficient mechanical properties as well as a negative temperature coefficient of coercivity TK (H_{cJ}). Mechanical properties of Nd–Fe–B composites can be improved by increasing the binder content or by doping their composition with the other metallic powders, e.g., iron powder.

Basic parameters of the bonded magnets manufacture are compacting pressure and curing temperature—for the pressing technology, and injection pressure and temperature—for the injection technology. In the case of pressing composites, the mixture of magnetic powder, binders, and admixtures is formed in the matrix under the pressure of 700–900 MPa. Next, the obtained compact is cured at temperature, which depends on the binder type. Using epoxy resin, the curing temperature ranges from 160 up to 200 °C, whereas in the case of injection composites, the curing temperature for polyamide is about 270 °C. The manufacturing parameters have a crucial influence both on magnetic and mechanical properties of bonded magnets, what is shown in Fig. 5 [19].

The injection temperature has a major impact on their mechanical properties (e.g., bending and compression strengths) of bonded magnets manufactured in the injection technology [20].

In the case of Nd–Fe–B pressing composites, an increase in the epoxy resin content improves their mechanical properties, but at the same time, it causes deterioration of magnetic ones and an increase in materials resistivity. Example of influence of content of epoxy resin is shown in Fig. 6 [19, 20].

The doping of the composition of Nd–Fe–B magnets with iron powder results in their higher hardness, as well as bending strength and compression strength.

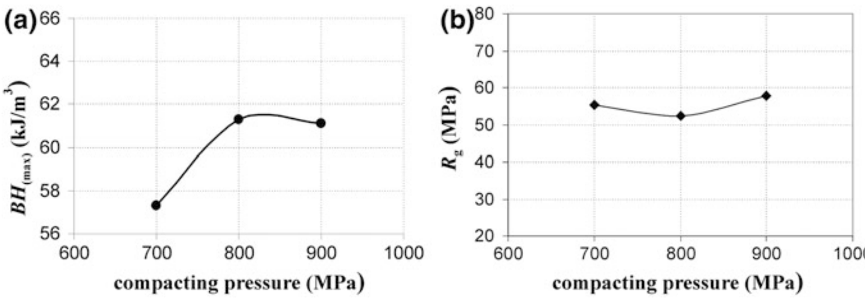


Fig. 5 The influence of the compacting pressure on the maximum magnetic energy product (**a**) and the bending strength (**b**) for the Nd–Fe–B bonded magnet [19]

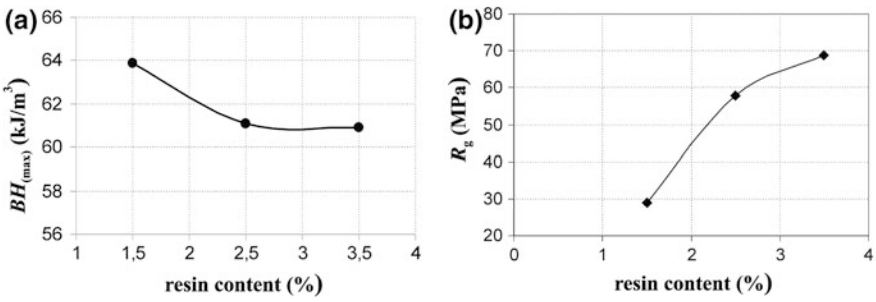


Fig. 6 The influence of the epoxy resin content on the maximum magnetic energy product (**a**) and the bending strength (**b**) for the Nd–Fe–B bonded magnet [19]

Table 2 The influence of iron doping on magnetic and mechanical properties of the Nd–Fe–B composite [28]

Iron powder content (wt.%)	Magnetic and mechanical properties				
	B_r (T)	H_{cB} (kA/m)	$(BH)_{max}$ (kJ/m^3)	R_C (MPa)	HBW (–)
0	0.724	448.5	84.6	112.1	35.0
5	0.694	385.9	66.1	118.8	36.6
10	0.690	349.8	62.6	130.6	37.1
15	0.684	314.0	51.8	136.2	37.7

HBW Brinell hardness, R_C bending strength

However, it worsens magnetic properties of the magnets. In particular, it makes magnetic coercivity significantly lower [9, 20, 28]. The influence of the iron doping on properties of the Nd–Fe–B composite is presented in Table 2.

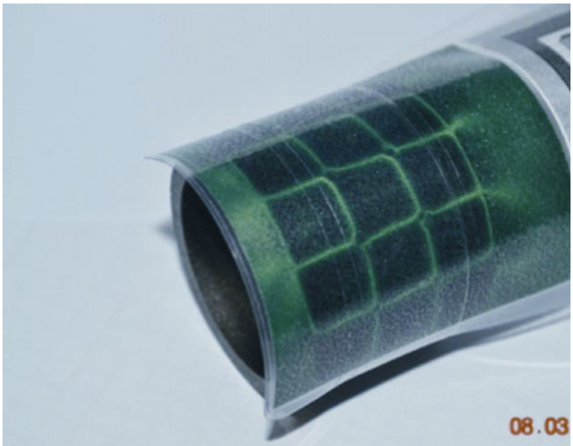
The iron doping of Nd–Fe–B magnets composition reduces the production costs. It should be noted that Nd–Fe–B composites doped by iron powder are placed between cheap ferrite magnets with weak magnetic properties and more expensive pure Nd–Fe–B composites. The appropriate doping of the bonded magnet composition allows tailoring their properties in order to adopting them to requirements of electric machine constructions.

A temperature coefficient of coercivity TK (H_{cJ}) has a major impact on working conditions of permanent magnets at high temperatures. A negative value of the TK (H_{cJ}) coefficient indicates that magnetic parameters become worse with increase of temperature. This property limits the use of bonded magnets at higher temperatures. The TK (H_{cJ}) coefficient can be improved by doping the composite composition with ferrite or AlNiCo powders, which have positive values of the TK (H_{cJ}) coefficient. However, a higher content of these powders causes significant deterioration of magnetic properties of bonded magnets [20, 21, 26–28].

The powder metallurgy, in particular, the bonding method, makes it possible to produce hybrid elements, i.e., elements having areas of different physical properties. These elements can be made from soft, hard or nonmagnetic powders.

Fig. 7 Samples of hybrid elements [20]

Fig. 8 Multipolar bonded magnets manufactured by Tele and Radio Research Institute



The manufacturing of hybrid elements in a single technological process allows the electric motors constructors to design new structures of magnetic circuits [20]. Exemplary hybrid elements made of soft (iron) and hard (Nd–Fe–B) magnetic powders are depicted in Fig. 7.

Hard magnetic composites might exhibit isotropic or anisotropic properties. Commercially produced composites are usually isotropic ones. These can be magnetized in all direction or/and even multipolarly. The sample of multipolar bonded magnet is depicted in Fig. 8.

4 Examples of Magnetic Composites Application

Soft magnetic composites are alternative core materials, comparing to soft ferrites and electrical steel sheets. Soft ferrites have lower power losses at higher frequency, but also lower values of saturation induction, what causes large dimension of

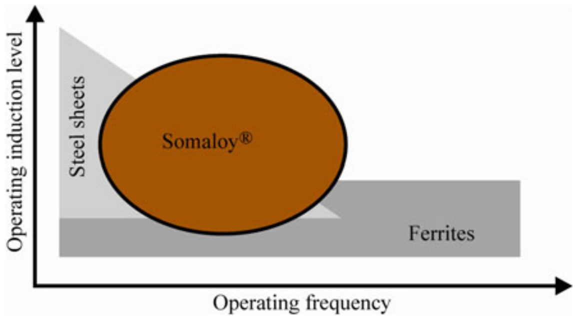


Fig. 9 Application areas of soft magnetic composites [29]

Table 3 Parameters of synchronous motors [32]

Parameters	Materials of stator cores		
	Fe–Si steel	Somaloy 500	Somaloy 500 (optimized core)
P_n (W)	10.66	10.66	10.66
M_n (mN m)	34	34	34
P_{Fe} (W)	3.72	6.78	4.57
η (%)	41	37	40.5

magnetic cores. On the other hand, electrical steel sheets have high values of saturation induction (about 2 T), but their application at higher frequency is restricted due to high values of power losses related to eddy currents. Soft magnetic composites due to unique combination of magnetic properties can be used in application areas restricted for conventional soft magnetic materials, what is depicted in Fig. 9 [29–31].

Direct replacement of a magnetic core made of conventional materials (soft ferrites or electrical steels) by a composite core is not effective, due to worse properties of magnetic composites comparing to conventional materials. The effective use of magnetic composites requires redesign of the electric devices, taking advantages and limitations of these materials into consideration [5, 7, 12, 23, 30–32]. In the case of a single-phase synchronous motor, a direct replacement of the stator core made of electrical steel by the composite core (Somaloy 500) of the same dimensions results in higher power losses and lower efficiency. The optimizing design of the stator core allows reducing power losses and increasing the motor efficiency [32]. Parameters of synchronous motors with different materials of a stator core are compared in Table 3.

Another example of soft magnetic composite applications is the yokeless stator of the disk motor with permanent magnets type YASA (Yokeless And Segmented Armature). In this construction, a stator yoke is replacement by the coils with cores made of Somaloy 3P. The motor bars can carry a no-load flux of 1.5 T and a peak-load flux of 1.8 T, which are under the saturation limit of the Somaloy 3P composite (about 2 T). This construction allows reducing the stator mass of 50% and obtaining the motor efficiency above 94% for a wide speed range. Moreover, the YASA motors have about 20% higher electromagnetic torque density, compared to typical constructions of disk motors with permanent magnets [33].

The optimized design of magnetic circuit constructions with the use of magnetic composites allows reduction in weight and volume of electric devices as well as for significant reduction of the number of used parts—only a few elements are required [6, 23, 25, 29–31], as depicted schematically in Fig. 10 [34].

Hard magnetic composites are generally used as permanent magnets in small electric motors. The main advantage of these composites is the ability to tailor their properties by doping the composition or by appropriate selection of manufacturing parameters. It can be presented for the 5 W DC motor with permanent magnet excitation, produced commercially by MIKROMA S.A. The motor body was equipped with the bonded magnets made of Nd–Fe–B powder and Nd–Fe–B powder doped with strontium ferrite powder. The magnetic properties of these bonded magnets are presented in Table 4. Each of the DC motors has different bonded magnets and rotor windings. An impact of the bonded magnet type on the motor operating parameters is presented in Table 5. The motor with permanent magnets made of the pure Nd–Fe–B powder and the 75 wt.% Nd–Fe–B + 25 wt.%

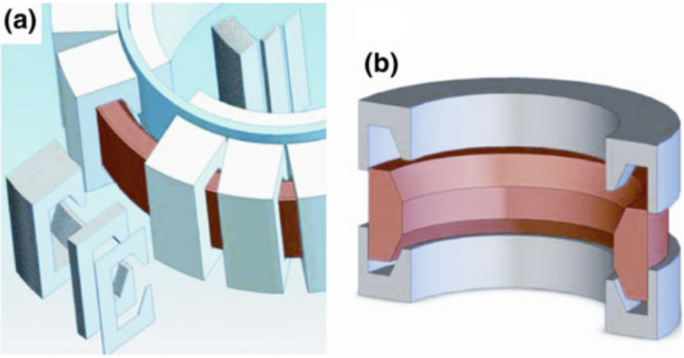


Fig. 10 Parts used in the tubular linear synchronous motor for magnetic circuits: made of electrical steels (**a**) and made of soft magnetic composites (**b**) [34]

Table 4 Magnetic properties of ferrite and composite magnets [27]

Magnet materials	Magnetic properties		
	B_r (T)	H_{cB} (kA/m)	$(BH)_{max}$ (kJ/m^3)
Sintered strontium ferrite	0.36	278	26.3
50 wt.% Nd–Fe–B + 50 wt.% strontium ferrite	0.30	192	15.7
75 wt.% Nd–Fe–B + 25 wt.% strontium ferrite	0.44	304	35.2
100% Nd–Fe–B	0.62	456	72.0

Table 5 Chosen operating parameters of the DC motors [27]

Magnet materials	Operating parameters					
	U (V)	*I* (A)	Torque (N m)	Rotation speed (rpm)	*P* (W)	η (%)
Sintered strontium ferrite	12	0.800	0.01	5000	5.00	52.0
50 wt.% Nd–Fe–B + 50 wt.% strontium ferrite	24	0.930	0.03	2911	8.93	40.0
75 wt.% Nd–Fe–B + 25 wt.% strontium ferrite	24	0.846	0.03	3700	11.38	57.0
100% Nd–Fe–B	24	0.750	0.03	3693	11.36	63.2

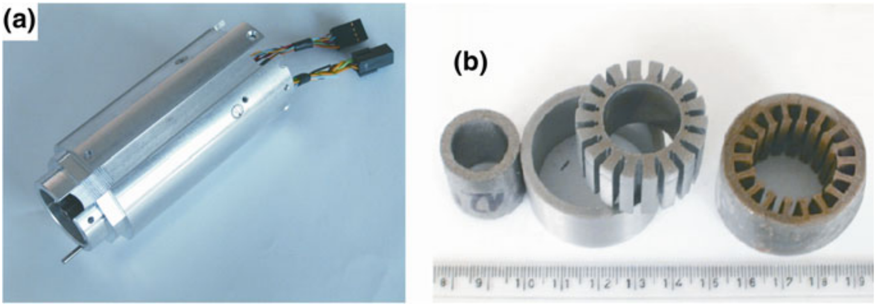


Fig. 11 The body of a DC brushless motor for electro-tools (**a**) and its soft and hard magnetic composites (**b**) [20]

strontium ferrite powder have the motor power higher than 11 W, whereas for the 50 wt.% Nd–Fe–B + 50 wt.% strontium ferrite powder—the motor power is about 9 W. In all cases, the achieved powers are comparable to the power of the commercial 10 W DC motor of larger dimensions. Thus, the appropriate selection of the bonded magnet composition and the rotor windings allows producing DC motors of the same body and different powers [27].

Summarizing, the research on properties and applications of soft and hard magnetic composites demonstrate that these can be successfully applied in electric motors for the automotive industry, electro-tools, household devices or battery operated trucks [19, 20]. Figures 11 and 12 show the exemplary brushless motors with elements made of magnetic composites. Both motors have passed operational tests.

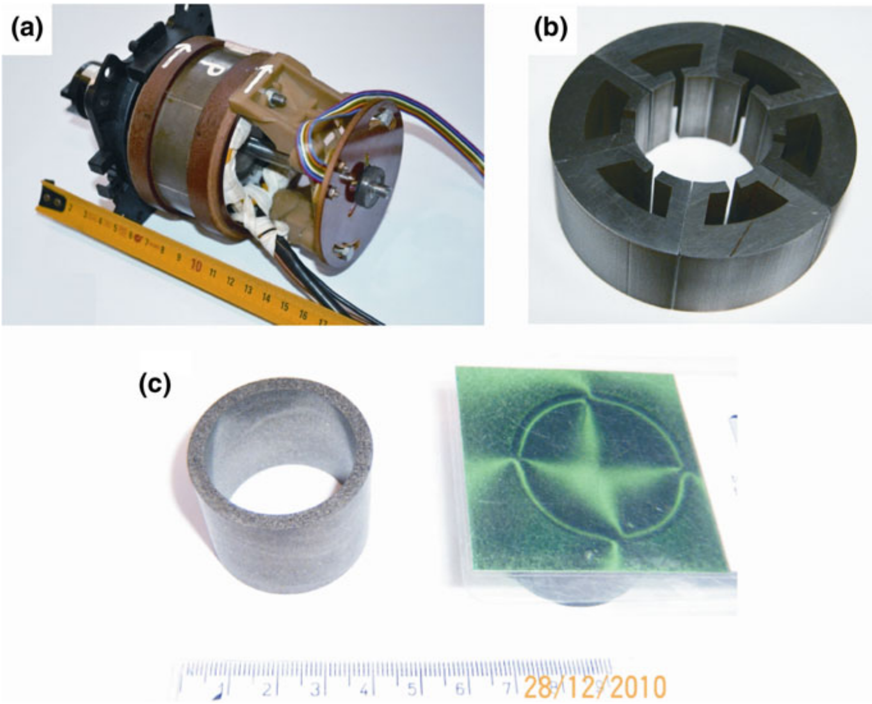


Fig. 12 A DC brushless motor for household devices (**a**), soft magnetic composites (**b**), four-pole permanent magnet made of Nd–Fe–B composite [19]

5 Conclusions

The paper shows properties of soft and hard magnetic composites as well as their advantages from applications in electric motors. Magnetic composites have a unique combination of magnetic and mechanical properties. Moreover, these properties can be tailored by the appropriate selection of the composition and the manufacturing parameters. The properties of magnetic composites allow the constructors to design new structures of their magnetic circuits, which are better adapted to the customer requirements and can allow reducing a size and weight of electric motors. The review of soft and hard magnetic composites shows designers of electric motors possibilities of applications of new types of soft and hard magnetic materials in future constructions of electric machines.

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