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Influence of resin type and content on electrical and magnetic properties of soft magnetic composites (SMCs)

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ABSTRACT

The magnetic cores of rotating electrical machines, such as electric motors and generators, are generally made using laminated steel sheets. However, in certain types of special electrical machines, such as servomotors that operate at high frequencies, it is possible to construct these cores into single solid blocks using the Powder Metallurgy (P/M) process. The advantages of using P/M include lighter machines that consume less energy and perform better. Thus, this work aimed to conduct a comparative study on the electrical and magnetic properties of some soft magnetic composites made from iron powder combined with different phenolic resins: HRJ-10236, SBP-128, SP6600 and SP6601, with mass percentages varying from 0.5% to 3.0%. The influence of different resin contents on the magnetic properties of the composites was analyzed, including relative permeability, saturation induction and the losses, as well as the electrical resistivity. The best results recorded were: saturation induction of 0.64 T for the composite Fe–RA0.5, electrical resistivity of 5020 μΩ m for Fe–RC0.5, magnetic hysteresis losses of 0.45 W/kg for Fe–RB0.5 and total magnetic losses of 0.30 W at 1 kHz, 20% lower than in laminated steel cores.

1. Introduction

Rotating electrical machines can function as a motor or generator and consist of two basic parts, namely the stator and rotor cores. These cores, with rare exceptions, are made from sheet metal (low carbon steel sheets) less than 1 mm thick that are stacked together. Some better performing machines, such as generators, are made from silicon steel sheets of approximately 3% silicon. The entire manufacturing process for these cores basically consists of lamination, stamping, electrical insulation between adjacent sheets, stacking and setting [1].

The rotor and stator cores are surrounded by windings powered by a sometimes alternating electric current, and are subject to the action of induced currents, also known as eddy or Foucault currents, which are responsible for appreciable power loss in these cores. The construction of these magnetic cores from electrically insulated steel sheets partially reduces eddy currents, representing the classic solution for minimizing eddy current losses. However, reduction of induced currents can also be achieved by increasing the electrical resistivity of the core material [1].

It is important to note that, in addition to eddy currents losses, magnetic losses in electromagnetic devices also include hysteresis loss. As such, alternative materials are currently being investigated to construct these cores as single solid blocks. Desirable primary characteristics for such materials are low hysteresis losses and high electrical resistivity. Moreover, they should also display high saturation induction and magnetic permeability, as well as sufficient ductility to withstand mechanical efforts and the vibration of electrical machine cores [1].

Soft magnetic composites (SMCs) obtained via Powder Metallurgy (P/M) are being used to replace the traditional stacked laminated steel employed in the rotor and stator cores of rotating electrical machines. The development of new SMCs aims to achieve more competitive magnetic properties, as with some types of small engines with complex geometry and servomotors that operate at high frequencies. It is important to underscore that electrical machine cores made from electrically insulated iron powders have some advantages over those constructed using laminated steel sheets, particularly as regards isotropic nature in conjunction with unique geometry possibilities, enabling three-dimensional designs [2,3].

Soft magnetic composite materials have two basic structures: resin-coated and microencapsulated materials, with some process variations possible. Resin-coated magnetic materials are a mixture of powders of ferromagnetic material, such as pure iron, and phenolic resin powders, typically thermoset. During this process, the iron powders and resin are mixed, compressed into dies and placed in ovens to

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Table 1
Resin specifications.

Specifications	HRJ-10236	SBP-128	SP6600	SP6601
Curing at 154 °C	50–90 s	30–65 s	15–30 s	15–30 s
Density (g/cm^3)	0.350	0.355	0.352	0.334
Hexamine content (%)	7.5–8.5	8.5–9.5	6.9–7.9	6.5–8.5
Granulometry (M# 200)	min. 97%	min. 97%	min. 97%	min. 99.9%

cure or plasticize the resin. Thus, the resins act both as an adhesive and electrical insulation between iron particles, increasing the electrical resistivity of the material and reducing Foucault currents (for use in electrical motor cores). In turn, microencapsulated materials consist of depositing some type of electrical insulation, such as a polymer or oxide, on the surface of iron powder particles in the form of films. The procedures employed to deposit insulation are kept secret by manufacturers. For the purpose of forming, the microencapsulated powders are compacted into matrices and placed into ovens for thermal treatment. A variation of both the aforementioned processes is compression molding, in which the forming and consolidation processes occur simultaneously [2,3].

The physical properties of soft magnetic composite materials used in rotating electrical machine cores are: magnetic and thermal isotropy, low eddy current losses when powered by a high frequency electric current, relatively low hysteresis losses when powered by a low frequency electric current, high electrical resistivity, low coercivity, small size and mass of rotor and stator cores and consequently, a reduction in the size of machines made from these composites [4–7].

SMCs have revolutionized certain fields of technology and are used in electronic devices, computers, the telecommunications and automobile industries, and have more recently been employed as magnetic materials in electromagnetic devices, such as rotating electrical machines (electric motors). The past few decades have seen the development of different magnetic materials, such as the sintered alloys Fe–Ni, Fe–Si, Fe–P, Fe–Si–P and Fe–Co. However, more recently, magnetic iron–resin composites have begun to replace these sintered alloys in some applications. Several aspects of the structuring processes of these composites have been studied and are topics of discussion among researchers, primarily in regard to their effects on magnetic properties and their applications in electromagnetic devices [8–10]. Effects of size and composition of powder particles, as well as compacting parameters (hot compacting, pressure, the use of lubricants — composition and percentages) are the subject of much study among researchers. With respect to microencapsulated materials, the latest research focuses on chemical and physical methods for creating thin layers of electrical insulation around the particles of metallic powders [3].

It is important to note that the application of powder metallurgy in the construction of rotating electrical machine cores is currently restricted to special electric motor cores. These include mini motors of complex geometry, for which efficiency is not the most important criterion, and some servomotors where armature windings are powered by a high frequency electric current reaching up to 1 kHz. Furthermore, from 400 Hz of electric power onwards, magnetic cores obtained by P/M processes show similar efficiency when compared to motors with laminated steel cores [11].

As such, the present study was conducted considering composites formed by iron with four types of phenolic resins. Thus, it was possible to compare the performance and physical properties of the four types of composites studied. The process used to obtain the samples consisted of mixing the powders, compacting and subsequent oven curing of the composite resins. Finally, magnetic properties, electrical resistivity and total magnetic losses were analyzed as a function of the electric current frequency of windings.

2. Materials and methods

2.1. Characterization of raw material and obtaining test specimens

The materials investigated in this study include composites obtained via P/M processes made from high purity iron powders and phenolic thermosetting resins. The iron powder was supplied by Höganäs Brasil Ltda and phenolic resins were acquired from SI Group Crios Ltda. Resins used were HRJ-10236 (RA), SBP-128 (RB), SP6600 (RC) and SP6601 (RD), whose main properties are displayed in Table 1. The iron powder exhibited the following characteristics: apparent density of 3.00 g/cm^3; green density of 7.16 g/cm^3 (at 600 MPa of compressibility) and granulometry: M# 180, 1,0%; M# 150, 7,6%; M# 106, 23.9%; M# 75, 22.5%; M# 45, 20.8; M# 0–44, 24.2%.

The iron powders were mixed with the four resin types cited, in mass proportions of 0.5%, 1.0%, 1.5%, 2.0%, 2.5% and 3.0%. Next, the powders were placed in a double cone blender for 20 minutes at 60 rpm for homogenization of the powder mixtures.

Compacting of the specimens into rings (Fig. 1a) was achieved using a hydraulic press at a pressure of 600 MPa, characterizing double effect

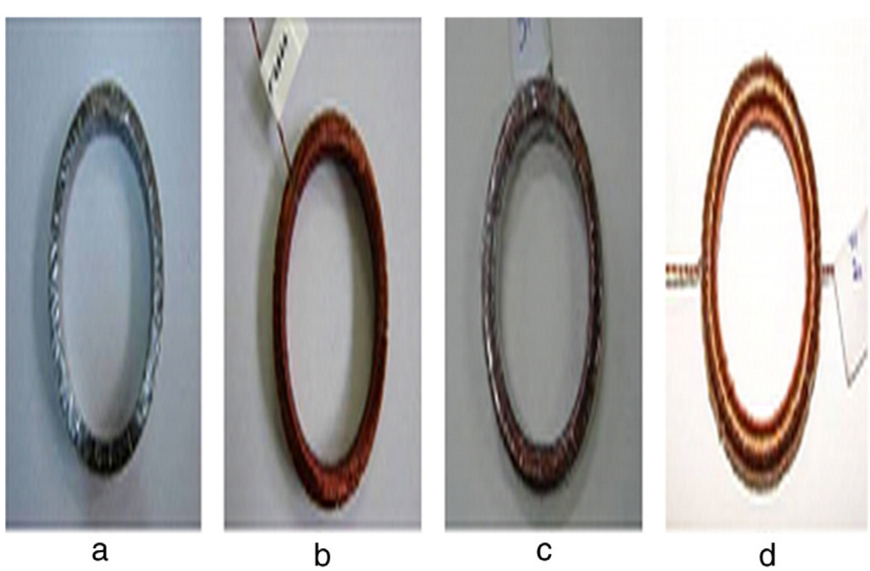

Fig. 1. Steps for specimen preparation: (a) insulation, (b) secondary winding, (c) insulation and (d) primary winding.

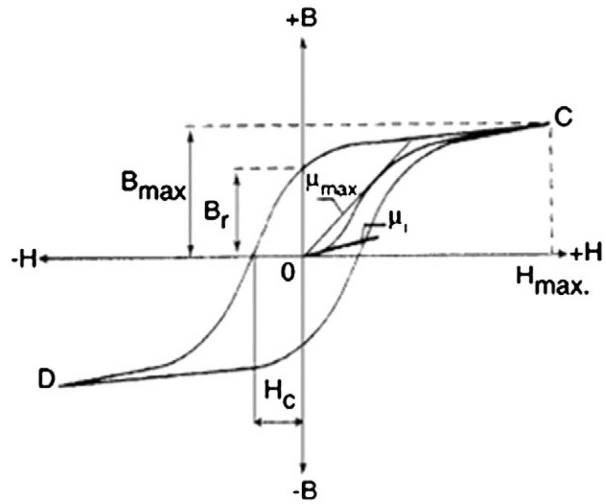

Fig. 2. Typical hysteresis loop of magnetic material and its observable properties [15].

compression. Resin curing was carried out in a muffle furnace, without a controlled atmosphere. According to data from the resin manufacturer, consistent curing begins with an initial curing period of 2 minutes at 90 °C, followed by two more minutes at 155 °C and, finally, two minutes at 220 °C. The ring-shaped specimens were machined in order to obtain the sizes recommended for characterization of their mechanical and electrical properties.

The use of a pure or pre-alloy metal is essential to obtain a metal–resin composite by P/M. For example, when using two or more different metallic powders or alloy elements in addition to the resin, simply curing the mixed powders would not allow for diffusion of the metals [12,13]. Thus, based on the process employed in this study, it would be impossible to use metal powder alloys by simply mixing these and submitting them to thermal treatment. Due to difficulties obtaining ferromagnetic alloy (or pre-alloy) powders, only iron–resin composites were used. It is important to underscore that the use of FeNi–resin composites was considered for this study. However, these could not be consolidated and require additional research since the FeNi powders used did not form metal alloys, but rather a simple mixture of iron and nickel powders.

As such, given that only iron–resin composites were analyzed, sintered iron was used as a reference for comparison against results obtained from composites. High density pure sintered iron has been extensively studied with respect to its different physical properties (mechanical, magnetic and electrical), displaying high magnetic saturation and relative permeability as well as low coercivity. These properties are essential for applications in the cores of rotating electrical machines. Some results for the composite properties investigated have also been related to the sintered allow Fe–50%Ni, since it also exhibits good physical properties suitable for use in the cores of electromagnetic devices [14].

2.2. Characterization of magnetic properties and electrical resistivity

The magnetic properties of iron–resin composites were obtained by analyzing hysteresis loops, which relate the magnetic field **H** applied to a material with the resulting magnetic induction **B** [15]. The method applied to assess magnetic properties in the present study is in line with ASTM standard A773, which describes the procedure for obtaining the hysteresis loop of ring-shaped materials (toroid) [16]. The device used was a TLMP-TCH-14 hysteresis loop tracer.

To apply this analysis method for magnetic properties, specimens must be prepared using copper winding wire, similar to voltage transformers with primary and secondary windings, in this case also known as a Rowland ring (Fig. 1). The procedure consists of: insulating the ring with plastic film to prevent peeling of the enameled wire, winding of secondary coils and additional insulation, followed by winding of the primary coils. Control parameters, such as electrical resistance in secondary winding, maximum electric current and frequency, are predetermined for each experiment. Electrical resistance was measured by a multimeter (approximately 1 Ω on average), with a current of 3 A and frequency of 60 Hz (frequency of the power grid).

Remanence (B_r) and coercivity (H_c) were obtained from the points that intercepted the horizontal and vertical axes, respectively. Fig. 2 shows the intercepts, with the values of H_c and B_r indicated in the graph. Maximum magnetic permeability (μ_{max}) and saturation induction (B_{max}) can be calculated by analyzing Fig. 2; however, these properties can also be obtained from the magnetization curve, without tracing the hysteresis loop.

Relative magnetic permeability (μ_r) was determined using maximum permeability, that is, the ratio between magnetic induction and the magnetic field applied, or the slope of the tangent line, as per Eq. (1).

$$\mu_{\max} = \frac{B}{H} \Rightarrow \mu_r = \frac{\mu_{\max}}{\mu_o} \quad (1)$$

where B is magnetic induction [T], H the magnetic field [A/m], μ_{max} maximum magnetic permeability [H/m], μ_r relative permeability, and μ_o magnetic permeability of the vacuum [15].

Hysteresis losses, Ph [W/kg], of the specimens were determined directly by the *TLMP-TCH-14* tracer, based on a calculation performed by the software of the device.

The electrical resistivity of the materials can be calculated based on the electrical resistance of specimens with known geometry and a length far greater than that of the cross-sectional area. An electric voltage is applied and the current measured. Electrical resistivity in the present study was determined using the electrical resistance of a ring (Fig. 1a), from which a segment was cut. This results in a specimen that is much longer than the cross-sectional area, or similar to a curved bar. Using Eq. (2), electrical resistivity was calculated as follows:

$$R = \frac{V}{I} \Rightarrow R = \rho_e \frac{l}{A} \therefore \rho_e = \frac{V}{I} \cdot \frac{A}{l} \quad (2)$$

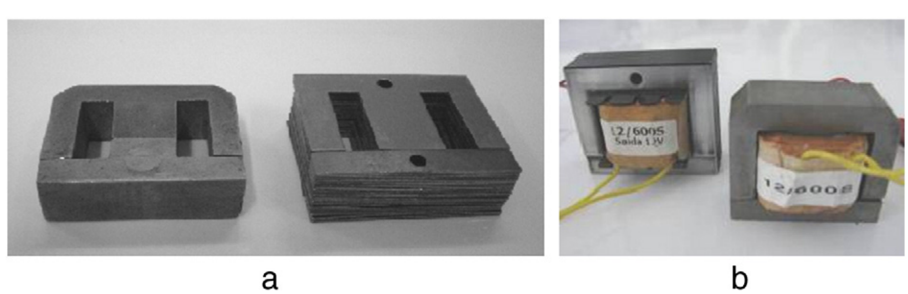

Fig. 3. Transformers — (a) Cores by P/M (left) and sheets (right) — (b) Wound and assembled by P/M (right) and sheets (left).

Table 2
Density of the composites before and after resin curing.

Sample Fe–RA	Density (g/cm^3)		Sample Fe–RB	Density (g/cm^3)		Sample Fe–RC	Density (g/cm^3)		Sample Fe–RD	Density (g/cm^3)	
	Pre-curing	Post-curing		Pre-curing	Post-curing		Pre-curing	Post-curing		Pre-curing	Post-curing
0.5	6.62	6.62	0.5	6.87	6.76	0.5	6.84	6.98	0.5	6.98	7.02
1.0	6.63	6.65	1.0	6.79	6.70	1.0	6.76	6.91	1.0	6.89	6.92
1.5	6.63	6.63	1.5	6.65	6.58	1.5	6.65	6.81	1.5	6.78	6.81
2.0	6.48	6.50	2.0	6.57	6.48	2.0	6.70	6.85	2.0	6.69	6.73
2.5	6.34	6.33	2.5	6.52	6.42	2.5	6.53	6.67	2.5	6.61	6.64
3.0	6.28	6.29	3.0	6.39	6.27	3.0	6.39	6.54	3.0	6.48	6.51

where ρ_e is electrical resistivity [Ω m], R electrical resistance [Ω], V electric voltage [V], I the electric current [A], A the cross-sectional area of the bar [m^2] and l the length of the bar [m].

2.3. Characterization of total magnetic losses as a function of frequency

Due to magnetic hysteresis and the circulation of eddy currents induced by the variation in magnetic flux inside the material, during magnetization reversal a dissipation of energy occurs, that is, magnetic losses, also known as iron losses. It is important to note that total losses in a rotating electrical machine include electrical losses in the windings of the rotor and stator cores (copper losses), magnetic losses in the cores consisting of hysteresis and eddy current losses (iron losses) and mechanical losses by ventilation and friction, in addition to other types of loss [1]. Given the importance of energy efficiency in electrical machines, and considering that iron losses are generally far greater than copper losses, magnetic losses are the main technical parameters for selecting and controlling these materials.

Total magnetic losses in the materials studied were evaluated using specimens in the form of cores E and T identical to conventional electric voltage transformer cores with the same size and windings. Thus, magnetic losses were determined in a similar manner to losses in a conventional transformer of the same size and with the same windings [1].

The cores in geometries E and T were obtained only for the composite HRJ-10236 (Fe–RA1.0), since all those studied showed similar behavior and this particular composite exhibited good general properties. The compacting and consolidation parameters applied were the same as those used to obtain the ring-shaped test specimens. After compacting and curing the E and T cores, these were submitted to rectification processes (Fig. 3a, on the left) to achieve the same dimensions as a conventional transformer core (Fig. 3a on the right). Next, the cores were wound in the typical manner of electric voltage transformers, with primary and secondary coils. Fig. 3b shows the assembled transformers, obtained from sheets (on the left) and Powder Metallurgy (on the right).

It is important to underscore that this study used a conventional low power and low voltage commercial transformer as reference. For the comparative study, cores were constructed using geometry and dimensions as close as possible to those of conventional cores. As such, windings in the cores developed were the same as those in the conventional transformer, which was disassembled and the coils removed from the spool. This procedure was applied to enable comparative analysis between the conventional transformer and those developed here.

The winding on the high voltage side was sized to operate at a voltage of 127 Vrms and the low voltage winding at 12 Vrms, considering conventional laminated steel cores. Tests were conducted using an alternating electric voltage source with variable frequency and amplitude, and a frequency range of 60 Hz to 1 kHz. The low voltage windings were powered by rated voltage of 12 Vrms, maintaining the high voltage winding open. This experiment is a typical open-circuit test, which results in magnetic losses in a ferromagnetic core. Next, the power supplied by the source was measured and losses from the primary winding were subtracted. The resulting power is directly related to hysteresis and eddy current losses. Due to the intrinsic analogy between the operation of rotating electrical machines and transformers, the same tests can be extended to the cores of electric motors.

3. Results and discussions

3.1. Test specimens and densities

Table 2 depicts the density values of the composites before and after resin curing for all the specimens. As shown, there is practically no change in density values for the Fe–RA composites, whereas Fe–RB exhibits a slight decline in this parameter. In turn, for Fe–RC and Fe–RD there was a slight increase in the density value. These results demonstrate the low impact of the curing process with regard to altering the density of composites.

3.2. Magnetic properties and resistivity

The hysteresis loops in Fig. 4 represent the behavior of two of the composites studied here (Fe–RA and Fe–RB), indicating the same behavior for these materials, that is, low saturation induction and low total magnetic losses. These loops were traced out at 60 Hz (the same frequency as the power grid and, therefore, the same as that of the electric currents in the machines to be developed from these composites).

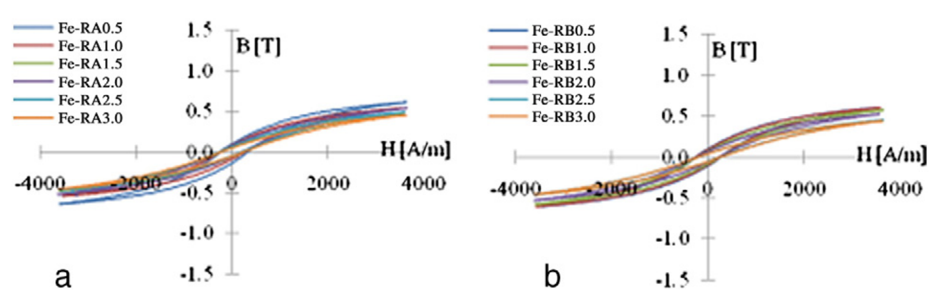

Fig. 4. Examples of hysteresis loops for the designated composites studied. (a) Fe–RA. (b) Fe–RB.

Table 3
Specifications of magnetic properties for the composites.

Composite	B_{max} [T]	B_r [T]	H_c [A/m]
Fe–RA0.5	0.64	0.10	272
Fe–RA3.0	0.45	0.04	223
Fe–RB0.5	0.61	0.10	261
Fe–RB3.0	0.45	0.04	255
Fe–RC0.5	0.63	0.11	280
Fe–RC3.0	0.43	0.05	271
Fe–RD0.5	0.58	0.11	260
Fe–RD3.0	0.42	0.04	243

Data analysis and the hysteresis loops were used to determine maximum magnetic induction (B_{max}), remanence (B_r) and coercivity (H_c) (Table 3).

Induction saturation or maximum magnetic induction was obtained using the maximum value of the hysteresis loop (maximum *y*-axis value). Based on Table 3, it was inferred that these composites display reduced B_{max} with higher resin content, ranging from 0.42 T for Fe–RC3.0% and from 0.64 T for Fe–RA 0.5%.

In a magnetization curve, with an increase in the magnetic field H, the induction value *B* rises rapidly, followed by a gradual increase until saturation. Fig. 5a and b show the magnetization curves, while Fig. 5c and d depict the permeability curves for the composites Fe–RC and Fe–RD. As can be observed, the curves for the composites display virtually the same characteristics in relation to the magnetic permeability curves and the slope of the magnetization curves, that is, both exhibit low values.

Relative magnetic permeability was determined for each composite studied based on the magnetic curves in Fig. 5 and Eq. (1), as per Table 4. It should be noted that relative permeability was calculated using maximum magnetic permeability.

With the increase in resin content, there is a continuous decline in permeability, although the Fe–RA composite with 2.0% resin exhibited an increase in this parameter. Based on the permeability values obtained in this study, it was concluded that these composites showed significantly lower relative permeability than the sintered alloys; for example, pure iron with relative permeability ranging from 2900 and 4700 and Fe–50%Ni with relative permeability of 21,000 [17]. These reference values were obtained for magnetic fields with very low frequencies, such as 0.05 Hz, almost at cc level (continuous current).

Table 4
Relative permeability of the composites as a function resin type.

Alloy	Maximum permeability, μ_{max}					
	0.5%	1.0%	1.5%	2.0%	2.5%	3.0%
Fe–RA	207	180	152	156	137	122
Fe–RB	205	200	179	160	121	117
Fe–RC	222	198	181	150	138	113
Fe–RD	207	182	156	130	118	105

Although soft magnetic composite materials display low permeability, which is not suited to use in electrical machines, they show considerably higher electrical resistivity when compared to sintered alloys, which is an excellent characteristic for application in electrical machines. Therefore, while there is a reduction in performance with respect to one characteristic (permeability), performance increases in relation to the other (resistivity).

Since most applications for iron–resin composites are in electrical machines operating on alternating current, different selection parameters must be considered for these materials, such as magnetic losses, which consist of hysteresis and eddy current losses. Given that magnetization is not a reversible phenomenon, the cyclic process to magnetize and demagnetize each half cycle takes 1/120 of a second, with a complete hysteresis loop occurring at 60 Hz, that is, every 1/60 of a second (complete cycle) [15].

Laminated steel sheets used in the rotor and stator cores of rotating electrical machines present an average magnetic hysteresis loss of around 1–7 W/kg, depending on several factors, including the alloy and structure of the steels used [1]. However, Fig. 6 shows that the materials investigated in this study displayed lower hysteresis losses when compared to laminated steels, decreasing with an increase in resin content. These reductions are shown in Fig. 6 as a function of resin content, varying from 0.29 W/kg (Fe–RD%3.0) to 1.69 W/kg (Fe–RD-0.5%), considering the maximum values. It is important to note that this behavior was maintained in additional studies, even at very low frequency or almost static conditions such as 0.05 Hz, with minimum variations in hysteresis loss for the composite materials analyzed.

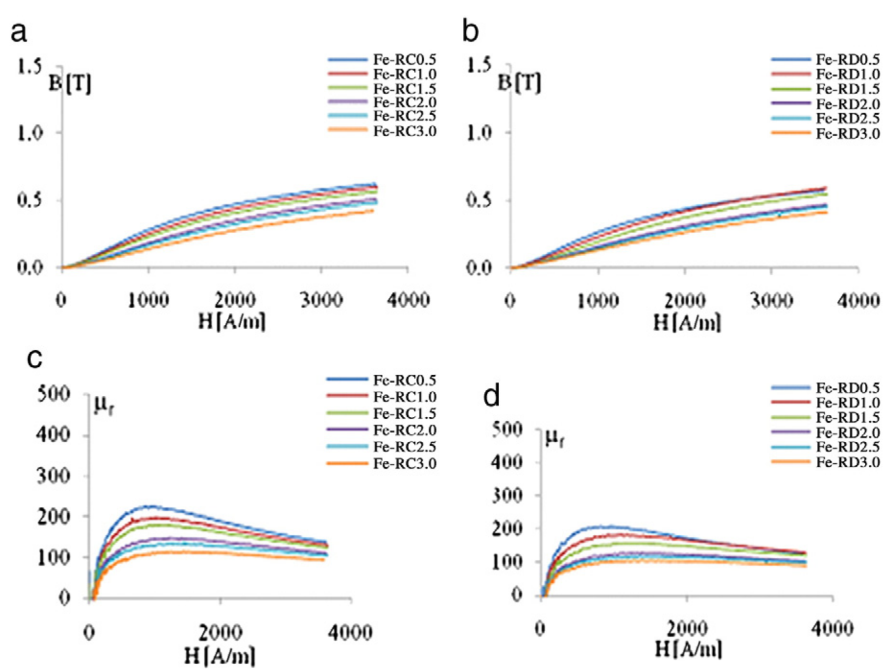

Fig. 5. Magnetic curves of the composites RC and RD. (a, b) Magnetization. (c, d) Permeability.

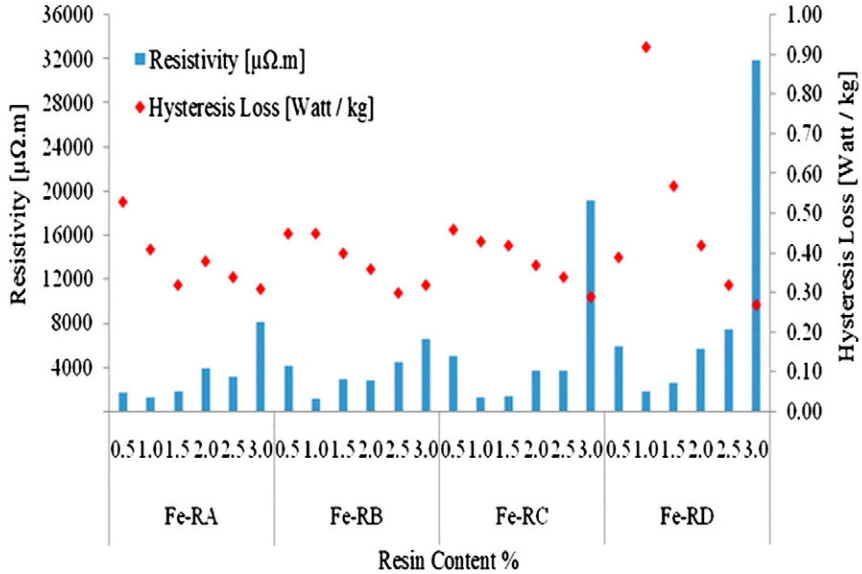

Fig. 6. Magnetic hysteresis loss and electrical resistivity as a function of resin content in the composites studied.

Electrical resistivity of the composites was calculated using Eq. (2). The graph in Fig. 6 illustrates the behavior of electrical resistivity. For the purpose of comparison, sintered pure iron displays resistivity values between 0.11 and 0.20 μΩ m, while resistivity values for the Fe–50%Ni range from 0.60 to 0.78 μΩ m [17].

Similar behavior can be observed for all the composites: resistivity decreases with an increase in resin content from 0.5 to 1.0%, but declines from this percentage onwards up to 3.0%. This is because when the resin content is close to 1.0%, the resistivity of the composite shows similar values when compared to the dense material (iron without resin), increasing from 1.0% resin and achieving very high resistivity at 3.0%.

In most cases, the resistivity of a metal element increases when impurities are added, since these cause alterations in the crystalline structure. As such, the highest resistivity is obtained in alloys consisting of two or more elements. In the examples provided, resin can be considered an impurity and, at the same time, act as an electrical insulator in the iron powder particles. These two divergent behaviors contribute to high electrical resistivity [17].

It is important to underscore that, in terms of total magnetic losses the previous considerations are only related to hysteresis loss. Total magnetic losses in a magnetic core include eddy current losses (induced or Foucault currents) and hysteresis losses.

As it may be seen in Fig. 6, with an increase in resin content there is both a rise in electrical resistivity and a decline in magnetic hysteresis losses, with both factors contributing to the good performance of the composite material when applied in the cores of rotating electrical machines.

Based on the results for electrical and magnetic properties, the composites with the best results for relevant properties for each type of resin are shown in Table 5. Since these composites demonstrate similar behavior with respect to low magnetic hysteresis losses and high electrical resistivity, while also displaying low relative magnetic permeability, maximum induction ($\mathbf{B_{max}}$) was used as a criterion to select the best composites.

However, in light of the low variation in maximum induction values, composites with high resin content can be used since elevated electrical resistivity of the material fulfills the requirements for its application. Due to its porous nature, this type of material is often more magnetically isotropic and suitable for electromagnetic devices [3,18].

The design of rotating electrical machines with these composites can include a three-dimensional magnetic circuit, with different topologies simulated in order to develop high performance electrical machines. This occurs because the magnetic flux in cores made from composite materials is not restricted to one plane as in laminated steel cores, which are generally used in the manufacture of machinery and electric transformers [18].

In regard to magnetic properties, the composites developed in the present study showed low saturation induction, up to 0.64 T, and maximum relative permeability of 222. These values are significantly lower than those found in laminated steel sheets and sintered materials used in magnetic cores, decreasing with an increase in resin content. By contrast, magnetic hysteresis losses are significantly smaller, with values up to ten times lower than those of laminated materials.

3.3. Frequency tests

Fig. 7 shows losses in Watts for cores in the shape of transformers, considering cores made from sheet metal, sintered metal (pure iron and Fe–50%Ni) and the composite material Fe–RA1.0 (Fe–1%HRJ), as a function of frequency varying from 60 Hz to 1 kHz. In light of the physical and structural differences between core materials, tests were performed using absolute losses in Watts for each type of core, whilst ensuring that the dimensions and consequently, the volume of the cores remained the same. It should be noted that measuring losses in

Table 5
Magnetic and electrical properties of the best performing composites.

Liga	Resistivity	Maximum Induction $B_{máx}$	Remanency B_r		Coercivity H_c		Losses [W/kg]	Maximum permeability
	[μΩ m]	[T]	[T]	[kG]	[A/m]	[Oe]		
Fe–RA0.5	1608	0.64	0.10	1.0	272	3.4	0.53	207
Fe–RB0.5	4048	0.61	0.10	1.1	261	3.1	0.45	205
Fe–RC0.5	5020	0.63	0.11	1.1	280	3.5	0.46	222
Fe–RD1.0	1772	0.60	0.17	1.7	660	8.3	0.92	182

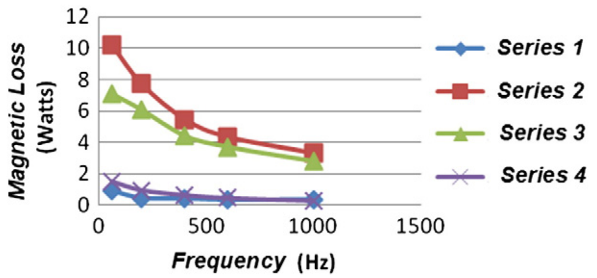

Fig. 7. Magnetic losses in voltage transformers with cores made from laminated steel (series 1), sintered materials (iron and Fe–50%Ni, series 2 and 3, respectively) and the Fe–1%HRJ composite (Fe–RA1.0, series 4).

ferromagnetic cores typically considers their mass, producing values in units of W/kg. Tests carried out on these transformer cores do not serve as absolute data, but rather for comparison between the materials analyzed. This is because the design of the transformer used as reference is unknown; for example, whether it operates at rated voltage with maximum magnetic flux.

It is noted that, whereas the sintered materials display an exponential decline in magnetic losses as a function of frequency, the laminated steel core shows almost no variation in magnetic losses for the same parameter. The core made from composite material exhibits a slight decrease in magenetic losses as a function of frequency, with very similar characteristics to its laminated steel counterpart, though presenting lower total magnetic loss than the laminated core for a frequency of 1 kHz. This test clearly demonstrates that these composite materials can be used in the cores of electromagnetic devices such as rotating electrical machines. However, a factor not considered, which is the goal of future research, was the tendency for the composite materials to exhibit a low power factor when used in the cores of electromagnetic devices, while laminated steel cores display a high power factor. At this point it is important to note that a low power factor generally reduces the performance of rotating electrical machines.

3.4. Temperature effects

In regard to the effect of temperature on the composites, it should be noted that rotating electrical machines operate at rated load with maximum internal temperature, determined by the characteristics of electrical insulators, such as the varnishes that electrically insulate the armature windings. This characteristic is denoted by the Degree or Classes of Insulation of electrical machines [1]. Thus, depending on the type of application of the machine, design engineers will define the degree of insulation and, consequently, the internal temperature of the machine. As such, the application of iron–resin composites in electrical machine cores is limited to machines with class A and B insulation (operating at 120 °C). This temperature range is well below the rate of degradation for the thermosetting resins studied (approximately 150 °C).

Preliminary studies indicated that the iron–resin composites (Fe–RAxx, Fe–RBxx, Fe–RCxx and Fe–RDxx) showed no measurable alterations in relation to magnetic, electrical and mechanic properties for temperatures below the rate of degradation for resin. This behavior is attributed to the nature of resins and the fact that no reactions occurred between the components of the composite.

In terms of electrical resistance, the predominant factor is electrical insulation caused by the layers of resin deposited between the iron powder particles; a characteristic that remains unaltered when the temperature rises. Magnetic properties are primarily influenced by the iron powder particles (ferromagnetic material of the composites) and are not subject to significant variations up to temperatures near 120 °C. With respect to mechanical properties, these are mainly influenced by the resin which literally binds or glues the iron particles and, since the resin remains stable until degradation, these properties also remain unaltered.

4. Conclusions

The material analyzed in the present study showed promising results for applications in the cores of rotating electrical machines. Furthermore, the addition of resin significantly increased the electrical resistivity of the soft magnetic composites, exhibiting values above 1000 μΩ m (5000 μΩ m for Fe–RC1.0). This elevated electrical resistivity reduces magnetic hysteresis loss for most of the composites studied, particularly when resin content increases. Hysteresis losses recorded were approximately 0.5 W/kg.

It is important to underscore that some parameters for specimen preparation influence the physical properties analyzed, including the granulometry of raw material, compacting pressure and curing cycle. This technology using P/M processes can also be employed in a number of applications, particularly in small engines or mini motors with complex geometry, replacing traditional laminated steel cores.

When powered by high frequency electric currents, the performance of electric motors with rotor and stator cores obtained by P/M processes (sintered and composites) is similar, or in some cases superior, to that of motors with laminated steel cores. It should be noted that some servomotors operate on a high frequency electric current, capable of reaching frequencies up to 600 Hz. Cores made from the Fe–1%HRJ composite showed magnetic losses 20% lower than those observed in laminated steel cores, at a frequency of 1 kHz. This aspect in itself justifies the use of these composites in servomotors.

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