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J. Electrical Systems 16-1 (2020): 67-76

Regular paper

Design and simulation of a stepper motor with cores obtained from sintered Fe50%Ni alloy

Journal of Electrical Systems

The objective of this work was the development of a three-phase, six pole stepper motor with stator and rotor core built from Fe50%Ni alloy via powder metallurgy. The study involves analysis of the magnetic, electrical and mechanical properties, besides motor design and software simulation using finite elements. The Fe50%Ni alloy showed as result an electrical resistivity of 0.37 □□˙m, relative permeability of 946 and maximum induction of 0.93 T. In the computational simulation, with the application of 1 A current per phase, the required voltage was 2.88 V, which resulted in a power of 2.88 W. In this condition the stepper motor generates a torque of 6.81.10-4 Nm with an air gap induction of 0.55 T.

Keywords: Powder metallurgy, electrical machine cores, simulation, stepper motor.

Article history: Received 14 July 2018, Accepted 1 July 2019

1. Introduction

Rotating electrical machines are fundamental devices nowadays. They can be found in countless applications that go from small mechanical drives until the generation of the electrical energy. The evolution of this equipment has been happening day after day, which has helped to popularize it's use. A rotating electrical machine has two forms of working as a motor or a generator. There are two basic parts of the machine that are the rotor and the stator. Each of these parts has a core which is usually constructed from thin metal sheets with a thickness of less than 1 mm, grouped into packages. Some of the best performance machines have their cores made of silicon steel sheets, with a percentage of approximately 3% silicon. The total process for making these cores consists of laminating, stamping, a step of electrical insulation between the adjacent sheets, packaging and fixing [1, 2].

The rotor and stator cores, depending on the configuration of the machine, are surrounded by windings fed by continuous or alternating current. Magnetic cores surrounded by windings fed by alternating electric current are subject to eddy currents, which are responsible for considerable losses. The construction of these magnetic cores from electrically insulated steel sheets partially reduces the eddy currents, consequently reducing losses. In some types of machines permanent magnets are placed instead of the rotor or stator windings [1, 2]. The computer simulation is a powerful ally for the realization of electrical machine design. From

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the data of the physical properties and the magnetic losses of the material it is possible to reproduce virtually the projected machine and to evaluate its performance.

The manufacturing process of the rotor and stator cores generate high costs, in addition to an excessive number of leftovers, around 40%, at the time the plates are punctured. In order to improve the utilization of raw material, making the production process more sustainable and increase the efficiency of electrical machines, powder metallurgy emerges as an alternative to the traditional process of obtaining the cores. Powder metallurgy is a relatively recent process of metallurgy processing, where the parts are obtained from the metal powders. Its main steps are mixing, compaction and sintering. Parts with specific requirements may needs a later finishing step such as rectification or surface treatment. From the specimens in different formats it is possible to perform the characterization of the desired alloy as its main physical properties of interest. The powder technology allows the construction of the cores in single massive blocks with high magnetic permeability and high electrical resistivity. The use of soft magnetic materials by powder metallurgy finds promising applications. Through the formulation of several alloys, new products are developed for application in electrical machines, aiming to improve factors that depend on both the chemical composition of the material and the microstructure. Currently the application of powder metallurgy to electrical machine cores is restricted to special electric motors, such as mini motors and servo motors, where performance is not the most important issue [3, 4, 5, 6].

The main contribution of this work is the study of Fe50%Ni alloy and construction of a three-phase, four-pole step motor with rotor and stator cores made via powder metallurgy. This alloy is characterized by high relative permeability, low saturation induction and high electrical resistivity, when compared to the alloys Fe, FeSi and FeP. Their properties make this alloy of interest in more sophisticated applications, operating at high frequencies and with low excitation, in which a very short response time is required. The study was performed analyzing the magnetic, mechanical and electrical properties of the Fe50%Ni alloy. The stepper motor project was based on another one whose has a scale three times smaller which is used in endoscopy surgery, constructed by the process of powder injection molding. Figure 1 shows the topology design of the simulated step motor.

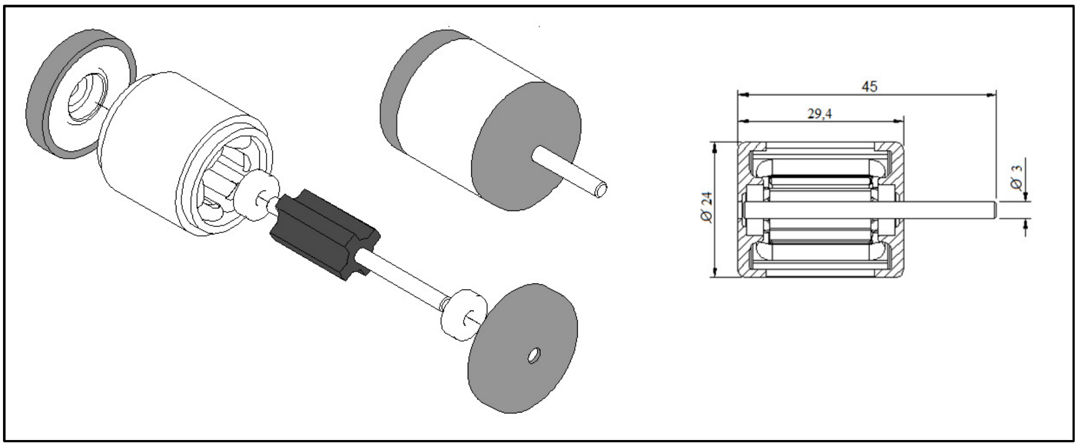

Figure 1 - Simulated stepper motor

2. Materials and Methods

Powder metallurgy is a relatively recent process of metallurgy processing, where the parts are obtained from the metal powders. Its main steps are mixing, compaction and sintering. Parts with specific requirements may needs a later finishing step such as rectification or surface treatment. From the specimens in different formats it is possible to perform the characterization of the desired alloy as its main physical properties of interest. For the use of a material in the confection of the core of electrical machines it is desired that the alloy has high relative magnetic permeability, electrical resistivity and induction of saturation, low magnetic coercivity and hardness compatible with the vibrations to which the machine will be submitted. In addition, it is important to know the magnetic losses that occur with the frequency variation to evaluate the behavior of the alloy.

2.1 Raw material

The two powders used as raw material were purchased from Höganas Brazil Ltda. According to the manufacturer's certificates, the iron powder used was ASC100,29, with 99.4% particle size between 45 μm and 150 μm. The pure nickel powder has a particle size between 3 μm and a maximum of 7 μm. The iron powder was used as the base powder and mixed with Ni to form the Fe50%Ni alloy. A double cone mixer, rotating at 60 rpm for 15 minutes, was used to mix the powders in order to homogenize the components. Also 1 % by weight of solid lubricant (zinc stearate) was added.

2.2 Specimens

The physical properties of the Fe50%Ni alloy were obtained from the preparation of different specimens for each test. The cylinder was used for the analysis of the mechanical properties, for the analysis of the magnetic and resistive properties was used the toroid form and for the evaluation of magnetic losses as a function of frequency was used the E an T transformer core shape. Figure 2 shows the specimens used.

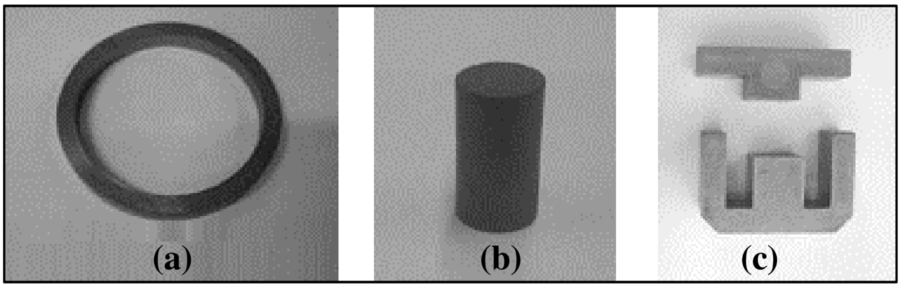

Figure 2 - Specimens (a) toroid, (b) cylinder and (c) E and T cores

The specimens were compacted in an EKA hydraulic press with a capacity of 40 tons. A compaction pressure of 500 MPa was used in all three specimen models. The sintering was performed in a furnace, with a controlled atmosphere of 95% nitrogen and 5% hydrogen. A heating rate of 15 °C/min was used up to the temperature of 500 °C, where the pieces remained for 30 minutes for the thermal extraction of the solid lubricant. After this time, the temperature was raised to 1,120 °C where the pieces remained for 30 minutes at this temperature. After this level, the oven was cooled slowly to room temperature.

2.3. Physical properties determination

The behavior of the physical properties of the material is fundamental part in the development of an electrical machine. Thus, the magnetic (coercivity, permeability and induction of saturation), electric (resistivity) and mechanical (hardness and metallography) properties of the Fe50%Ni alloy were evaluated based on international standards.

Magnetic permeability and saturation induction were obtained from the magnetization curve. The tests were performed using the hysteresis curve tracer device model TLMP-TCH-14, manufactured by the Globalmag and followed the ASTM A773 standard [7, 8].

The electrical resistivity was measured by the acquisition of the values through the application of an electric current of known value and measurement of the voltage at the terminals of the test body with the multimeter. The electric current was applied from a Vcc source Jomed model OS-2403D and measurement of the resulting voltage value. From these values was used the equation that relates the electrical resistivity of a material with the voltage, applied current, cross-sectional area and length of the test body.

Finally, the tests to evaluate the mechanical properties of the alloy were performed in a Precision - England hardness measuring instrument, Rockwell B hardness (HRB. The hardness tests followed ASTM E10 standard. The metallographic analysis of the surface microstructure of the test specimens was performed in a JSM-6510 LV Scanning Electron Microscope equipped with a Thermo Scientific Ultra Dry 6742A-1UES-SN X-ray energy scattering spectrometer (EDS) [9].

2.4 Magnetic losses determination

The losses in the studied material were determined from specimens with E and T shapes, identical to the cores of conventional electric voltage transformers of the same dimensions and windings. This allowed the tests to be performed in a manner similar to the tests for losses analysis in a conventional transformer with laminated plate core [1, 2].

After compaction and sintering, the E and T cores were milling to be the same dimensions of a conventional electric transformer core. Next, the cores were wound in the typical form of electric voltage transformers, with primary and secondary winding coils. Using a conventional low voltage and power commercial transformer as base, the windings used in the developed transformers were the same as those of the conventional transformer. This procedure allowed a comparative analysis between the conventional and the developed transformer.

The winding on the high voltage side was designed to operate with a voltage of 127 Vrms and the low voltage winding with 12 Vrms, considering the core of conventional plates. The tests were performed using an alternating voltage source with amplitude and frequency variation, which was 60 Hz to 1 kHz. The low voltage side winding was fed at a voltage close to 6 Vrms (half of the nominal winding voltage), keeping the high voltage side winding open and varying the amplitude from the low voltage side to the high voltage side reach 75 Vrms. Next, the power supplied by the source was measured and the losses in the winding were discounted. The resulting power is directly related to losses in the cores by eddy currents and hysteresis cycle. After, a load was placed on the output of the transformer in this configuration. To determine the magnetic losses in the cores, the dissipated power in the load and the loss in the secondary winding must be discounted.

2.5. Computational simulation

The design of stepping motor developed was based on physical principles and functioning of a reluctance machine with stator windings connected as unipolar. Figure 3 shows the (a) rotor and (b) stator designs of the motor. Figure 4 presents a (a) cross-sectional view, while (b) indicates the external dimensions of the engine. The winding and current characteristics used for simulation were: 33 AWG gauge wire winding; 59 turns for each pole (118 per phase) and current of 1.0A. The drive was defined with three phases (A, B and C). Considering six poles on the stator, i.e. two poles per phase, one has a displacement of 60°.

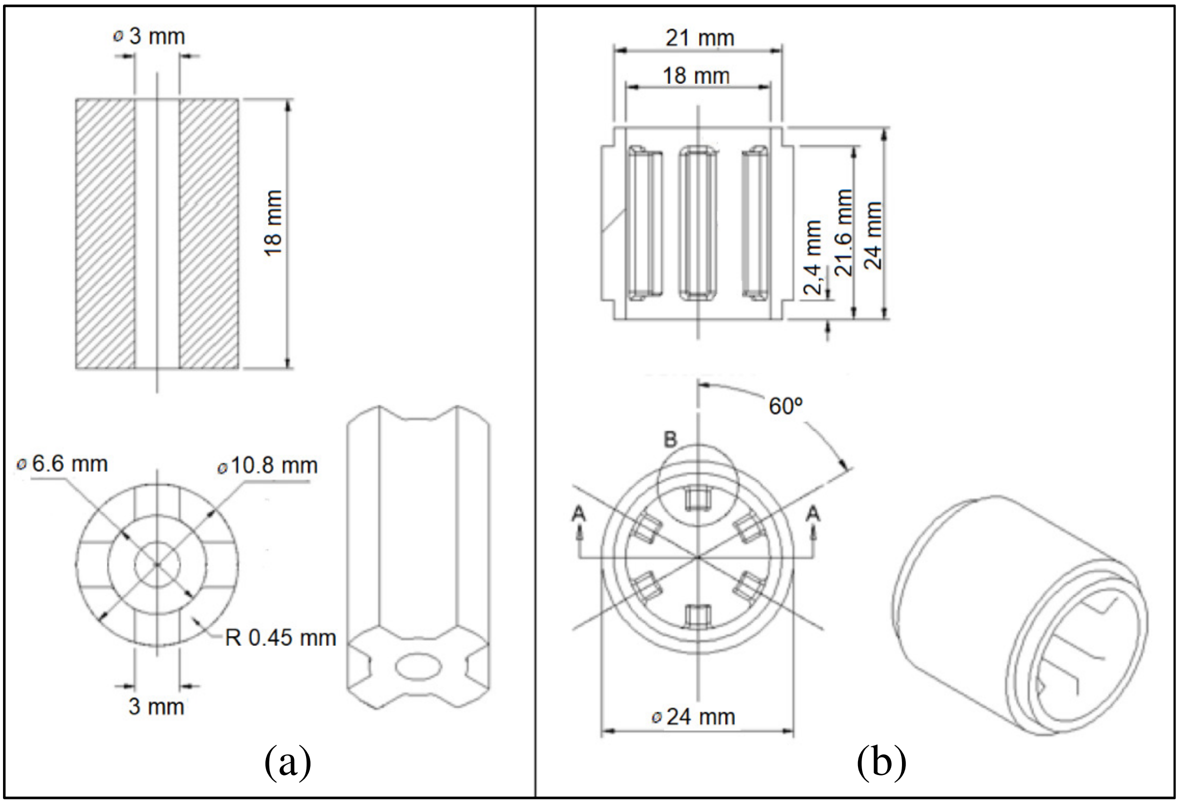

Figure 3 - (a) rotor and (b) stator of stepper motor

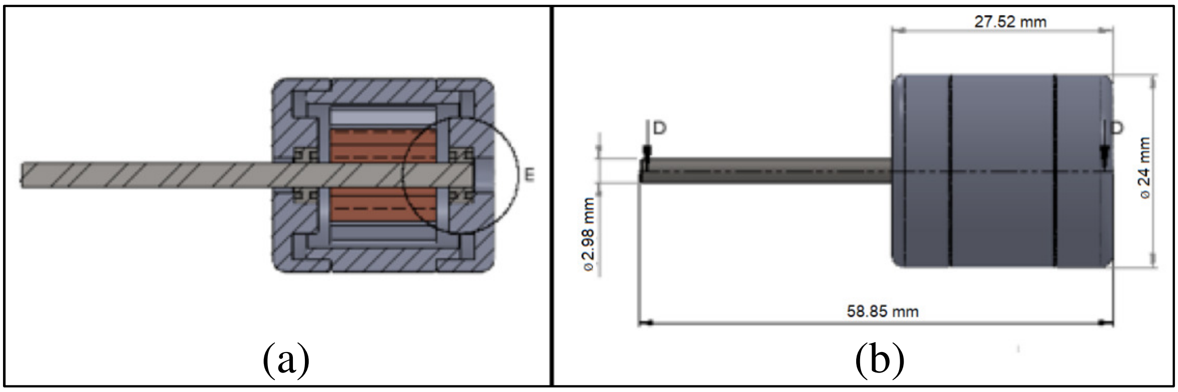

Figure 4 – Motor (a)cross-sectional view (b) external dimensions

Figure 5 shows (a) the detailing of the pre-processing of the simulation and (b) the detail of the mesh used to plot the magnetic flux inside the motor.

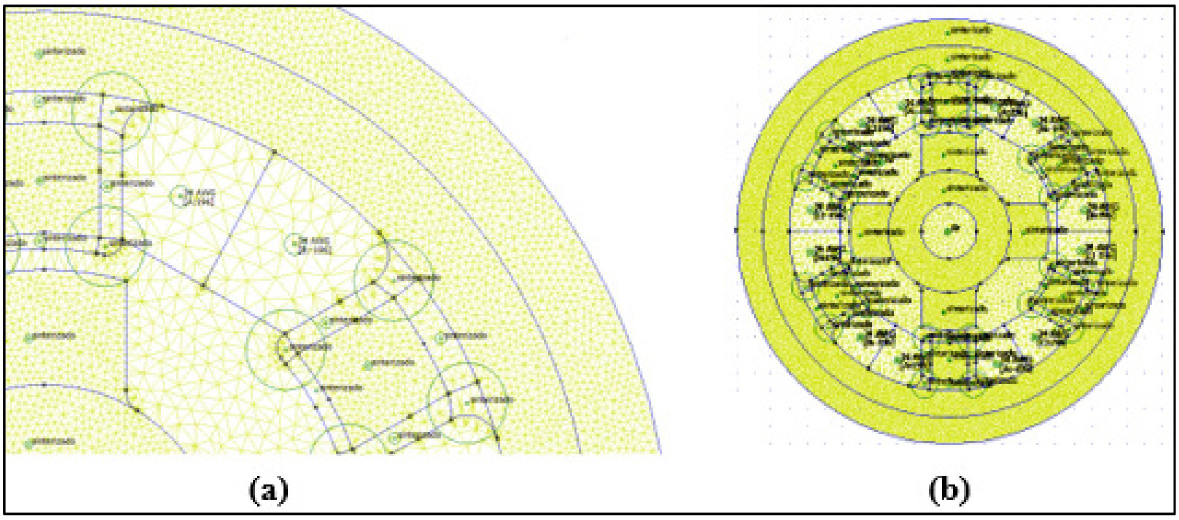

Figure 5 - Detail of the simulation (a) pre-processing and (b) the mesh

3. Results and discussions

The information collected during the tests indicates the behavior of the Fe50%Ni alloy in relation to its physical properties, magnetic losses and theoretical operation as material of the stator and rotor cores. All the tests were performed on three different specimens so that an average value was found.

3.1. Physical properties of specimens

The first evaluation performed on the specimens obtained from Fe50%Ni alloy was the green density measurement. The density before the sintered material was 6.63 g/cm3. After sintering, the average density resulted in 7.25 g/cm3. The literature indicates that pieces composed of this alloy have a final density varying from 7.1 to 7.4 g/cm3, similarly to the density of sintered pure Fe (7.2 g/cm3) [10, 11].

From the hysteresis curve it was possible to obtain the retentivity and coercivity values of the material. The results indicated a retentivity of approximately 0.22 T and coercivity of approximately 112.1 A/m. The literature indicates a retentivity of 0.80 T and a coercivity of 20.0 A/m for this alloy. For the purpose of comparison between materials, sintered pure iron has an approximate retentivity of 1.18 T and a coercivity of approximately 127 A /m. Figure 6 shows the hysteresis curve of the alloy [3, 10, 11, 12].

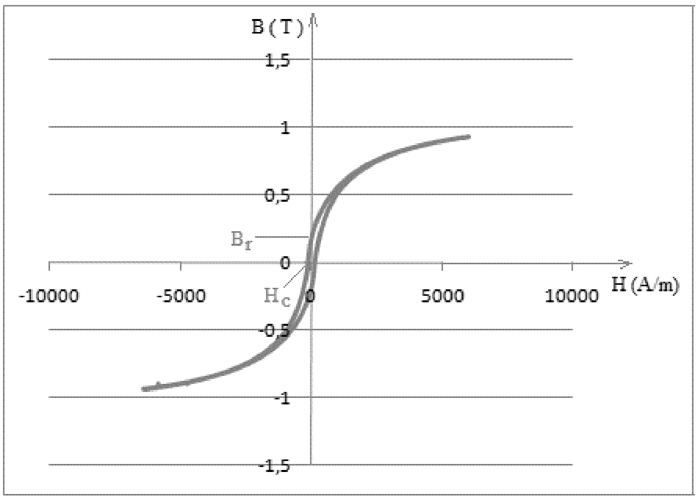

Figure 6 - Fe50%Ni hysteresis curve

The relative magnetic permeability of the alloy was obtained from the magnetization curve. It is the ratio between the magnetic induction (B) and the applied magnetic field (H) or the slope of the tangent line. Figure 7 shows the resulting magnetization curve of the alloy, where maximum induction was observed for a magnetic field of 6 kA/m. The relative (maximum) magnetic permeability resulted in 945.6 and the maximum induction in 0.93 T (references present values of 21.000 and 1.09 T respectively) [3].

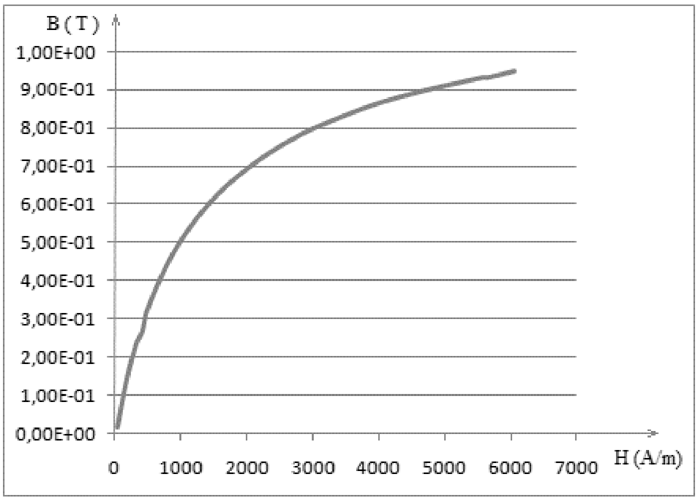

Figure 7 - Fe50%Ni magnetization curve

The electrical resistivity of Fe50%Ni alloy was performed using the same specimens used in the magnetic assays. A small segment of the toroid was removed and then welded wires to the application of the electric current and measurement of the resulting voltage. The mean of the specimens resulted in an electrical resistivity of approximately 0.37 $\mu\Omega \cdot m$. According to the literature reference, the alloy presents a value of 0.69 $\mu\Omega \cdot m$ and the sintered pure iron presents an approximate electrical resistivity of 0.12 $\mu\Omega \cdot m$. Greater electrical resistivity is desired for use in electric motor core as it reduces eddy currents [3, 10, 11].

The hardness test resulted in an average value of 101 HRB. The production of the cores of an electrical machine with powder metallurgy may require a subsequent machining process for dimensioning after sintering. Therefore, materials with high hardness are not recommended. The Fe50%Ni alloy showed hardness values similar to steel SAE 1008, which is around 95 HB. This steel is widely used in the construction of the cores of most rotating electrical machines [1, 2].

For the analysis of the microstructure of the specimens, the segments of the toroid removed in the analysis of the electrical resistivity were used. Samples were embedded, sanded and polished. The etching was carried out using the Marble reagent (4g $CuSO_4$ + 20 ml HCl + 20 ml distilled water). Figure 8 shows the microstructure of the alloy studied. As can be observed, the Fe50%Ni alloy presented some pores on the surface of the sintered part.

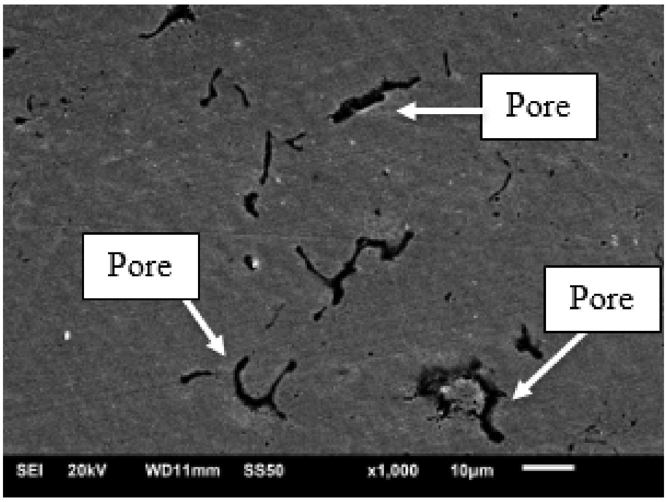

Figure 8 - Microstructure of a sample of Fe 50%Ni obtained by scanning electron microscopy

3.2. Magnetic losses results

From the results of the frequency loss test for the transformer core built with powder metallurgy it was possible to observe that the losses due to eddy current and hysteresis decrease drastically up to approximately 400 Hz. After this frequency value a tendency of the losses occurred stabilize as the frequency increases. For sheet cores, losses have remained constant as a function of frequency. As the frequency increases the induced voltage increases, the magnetizing current decreases and, in this way, the losses would be lower for the cores constructed with laminated sheets. However, at frequencies above 400 Hz, the effect of the construction of the laminated sheet core does not reduce the eddy currents, as compared to sintered core, i.e. the induced voltage increases and the magnetizing current decreases, but the eddy currents increase. In the sintered core, only the induced voltage increases, the magnetizing current decreases and the eddy currents do not increase in value. Figure 9 shows the graphs of losses in Watts for frequencies from 60 Hz to 1 kHz for the specimens.

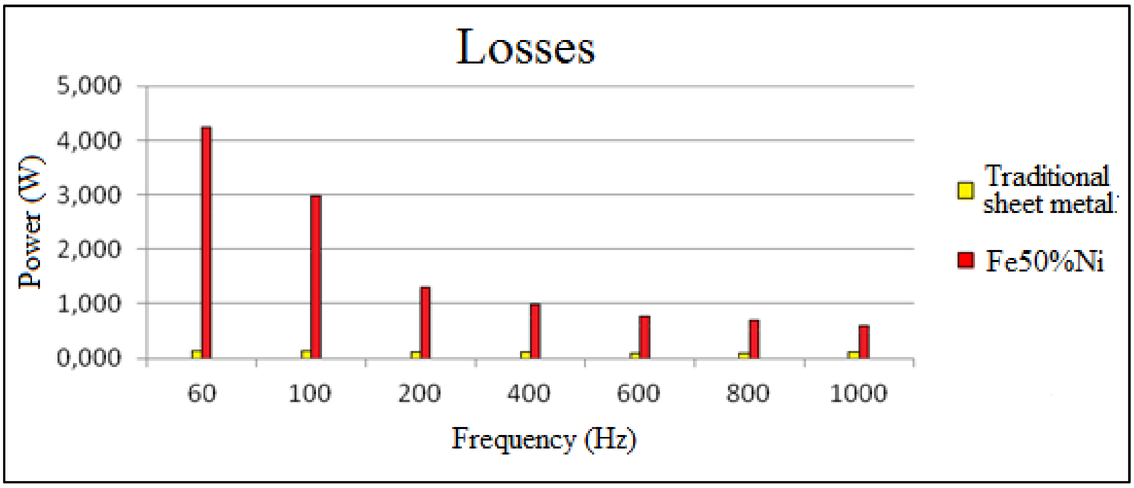

Figure 9 - Magnetic losses in transformers with sheet cores and Fe50% Ni

3.3. Results of the simulations

The simulation of the proposed electrical machine was performed in FEMM 4.2 using a current of 1.0 A. Table 1 shows the results of the electrical and magnetic quantities obtained from the simulation, considering the three phases (circuits A, B and C). It is observed that the currents in circuits A and C are zero, since in this type of drive, only one circuit (or two coils) are fed in turn, switching to another circuit in the next cycle. For half-step drive the two-circuit coils are fed simultaneously and only one circuit remains at zero amperes.

Table 1 - Electrical and magnetic quantities obtained from the simulation

	Current (A)	Voltage drops (V)	Air gap flow (Wb)	Inductance (H)	Voltage/current (Ω)	Power (W)
Circuit A	0.00	0.00	$2.33 \cdot 10^{-4}$	0.00	0.00	0.00
Circuit B	1.00	2.88	$6.38 \cdot 10^{-4}$	$6.38 \cdot 10^{-4}$	2.88	2.88
Circuit C	0.00	0.00	$1.36 \cdot 10^{-4}$	0.00	0.00	0.00

Figure 10 shows the result of the electromagnetic interactions in the machine with 1.0 A, in which the axis of the abscissa shows the linear representation of the air gap and the axis of the ordinate shows the magnetic flux density. Observation of the air gap flow allows to verify if the machine operates at maximum flow and if the rotor and stator cores are not magnetically saturated [1, 2].

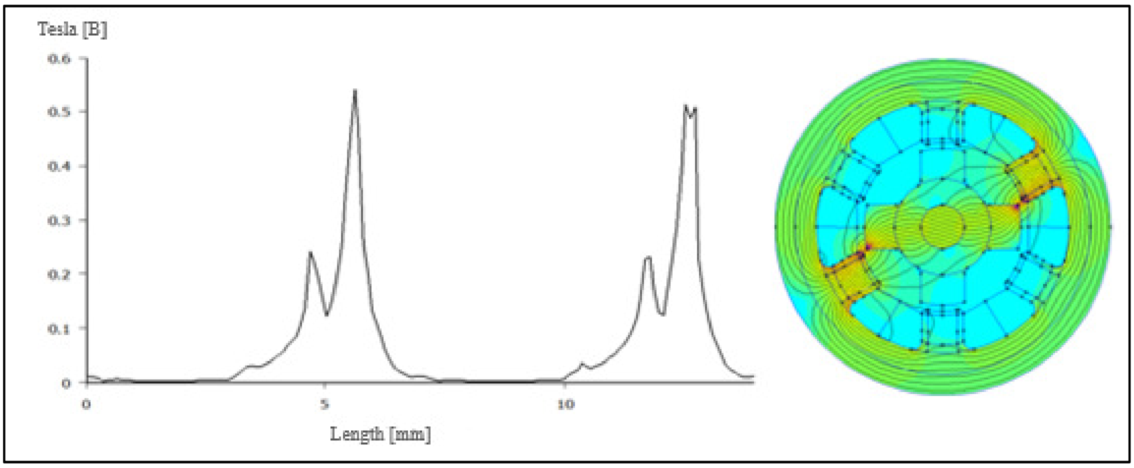

Figure 10 - Air gap flow density with 1.0 A

The magnetic induction of air gap presents maximum values between 0.5 to 0.55 T for 1.0 A supply. The torque developed at the tip of the motor shaft is proportional to the magnetic flux of the air gap. The simulation indicated a resulting torque value of $6.81 \cdot 10^{-4}$ Nm. A rotating electrical machine, depending on the configuration, can work with air-gap flows much higher, in the range of 1 to 1.5 T. The air-gap flux can be increased by increasing the electric current of the coils, however, the intensity of these current is limited by the wire gauge used in the winding [1, 2]. Therefore, by resizing the coils (wire diameter and winding numbers) and electric current, for the same topology, it is possible to obtain a higher torque than the current one. Still observing Figure 8, it is possible to say that because the magnetic parts of the mini motor are not saturated, there is a possibility of increasing the magnetic flux of air gap.

4. Conclusions

The Fe50%Ni sintered alloy used did not present the magnetic properties and electrical resistivity indicated in the literature, since a pre-alloy powder was not used, but an alloy based on the mixture of iron with 50% of nickel. An alloy obtained by casting or mechanical-synthesis would have better properties, although the mechanical properties are within the parameters of the steels used in electric motor cores. However, it presented a relatively narrow hysteresis cycle, with low values of magnetic induction of retentivity and coercive magnetic field, proving to be suitable for use in rotating electrical machine cores [2]. From the hardness tests carried out, it can be verified that the specimens obtained with sintered Fe50%Ni alloy have a low hardness, similar to cast iron and most non-ferrous metals [7], such as aluminum and the brass having value corresponding to the class of metals of easy machinability, although it contains Ni in its composition. Regarding the losses in the cores, the tests carried out showed that the sintered Fe50%Ni alloy becomes interesting for magnetic flux frequencies above 400 Hz, because below this frequency the yield becomes very low when compared to the sheet metal cores. The simulations carried out with the FEMM 4.2 showed that the magnetic interactions between the rotor-stator assembly will not have bigger problems, since high saturation levels of the magnetic fields were not verified. The behavior of the magnetic flux density showed adequate behavior to the expected, the same occurring in relation to the behavior of the magnetic potential with its quasi-sinusoidal waveform.

The reconstruction of the engine with a pre-alloyed Fe50% Ni and re-winding would result in a significant improvement in engine performance, although in the drive tests, it turned accurately and without oscillations in pulse train frequencies between 2 Hz and 5,5 Hz, after this value, the synchronism was lost. Thus, the maximum speed obtained in the stepper motor was 333 rpm. Tests as angular positioner have resulted in precise displacements with locking torque. It should be noted that in this step motor topology, the micro-pitch drive could be used provided that another PWM (pulse-width modulation) drive circuit is used to feed two adjacent coils, which would result in steps of proportional angles proportional to the voltages generated in each of the adjacent coils.

Acknowledgment

Authors gratefully acknowledge the support of FINEP, FAPERGS and CNPq.

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