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Regular paper

Study of synchronous machines with permanent magnets and sintered core for wind turbines application

This work aims to present the study of synchronous electrical machines with permanent magnets for use in wind turbines, where the rotor, usually built from laminated sheets of low carbon steel and FeSi, will be replaced by sintered alloys obtained from Powder Metallurgy. Thus, in this work, studies will be conducted in order to verify the feasibility of using pure iron and some sintered alloys, such as FeSi and FeNi, to construct the referred rotor. These materials will be characterized in terms of their physical properties as well as simulations of the machine will be carried out in three different topologies of the rotors. Two machines have the magnets bonded to the surface of the rotors, with two different configurations, namely straight poles and poles protruding, and the third one has the magnets inserted inside the rotor core. The simulations results of different topologies pointed out that for machines with rolled sheet, the best sintered alloy in order to replace the rotor core would be Fe-2%P. The worst case would be the machine with magnets embedded, having the other two similar torque results.

Keywords: Synchronous Electrical Machines; Powder Metallurgy; Soft Magnetic Materials.

1. Introduction

Rotating electrical machines can function as a motor or generator and have two basic parts that are the core of the stator and rotor. These cores, with rare exceptions, are currently built from thin metal blades (low carbon steel sheets) with thickness less than 1 mm, grouped into packages of sheets. Some higher-yielding machines such as generators are built with silicon-steel sheet, with percentage of approximately 3% of silicon. The overall process for preparation of these cores concerns basically in lamination, stamping, a process for electrical insulation, packaging and fixing. With respect to the low-carbon steel sheets, the insulation process consists of a thermal treatment, where the packets of plates are placed into ovens for a certain time, leading to the oxidation of the surface of the plates and, consequently, there is the formation of an insulating layer of iron oxide between adjacent plates. Some types of silicon steel sheets are supplied by manufacturers with a paint based on oxides on their surfaces [1, 2].

Magnetic cores surrounded by coils, where alternate currents circulate, also generate an alternating magnetic flux. For this reason, these cores are subjected to the action of eddy currents, known as Foucault currents, that are responsible for significant loss of power in these cores. The construction of these ones from steel sheets electrically insulated partially reduces the eddy currents, minimizing the losses by Foucault current [1, 2].

Regarding the construction, changes in shape and drive of the electric machines are on the limit of technological improvement and only drastic changes in the materials used to

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construct the cores of the electric machines will result in improved performance of that. The same occurs with respect to the drive, where devices from semiconductors, such as inverters, are also within the limits of technological improvement.
However, using the processes of powder metallurgy (P/M), it is possible to build these cores in massive single blocks with high magnetic permeability and a higher electrical resistivity if compared to conventional steel, leading to the reduction of the eddy currents [3, 4]. In the case of application of this process in the construction of cores of rotating electrical machines, it can result in machines with some advantages over those with conventional cores. Thus, insofar as it is possible to construct cores in single massive blocks, fewer steps will be present in the construction of the machines and, naturally, less energy will be consumed in the fabrication of such machines. It should be also mentioned that, using magnetic alloys with higher resistivity in the construction of stator and rotor cores, there will be a reduction in eddy current loss, higher yield, thereby resulting in electricity savings.
Currently the application of P/M in cores of electric machines is restricted to special motors where the yield is not the most important criterion, as in the case of minimotors with complex geometry, in some servomotors where the armature windings are supplied with electrical current of high frequency, and parts of machines where there is no change in magnetic flux, as rotor core of synchronous machines. However, some studies are being conducted in other types of machines obtained from the P/M in order to prove or dismiss the application of this technology in these machines.
Thus, this work aimed to study and to test soft magnetic materials obtained from combined iron powder with phosphorus, silicon and nickel and its application in cores of rotating electrical machines with supply of armature three-phase currents, replacing the traditional laminated steel sheet packs. After characterizing of various sintered alloy, a study was performed with three topologies of rotors of synchronous electrical machine with permanent magnets [1, 2, 5, 6].

2. Electrical Machines By Powder Metallurgy

2.1. Processes of Powder Metallurgy and its variations

Some special types of electric motors have rotor and stator cores, which are made with metal powders, using Powder Metallurgy, or its variations:
Conventional Powder Metallurgy: P/M is a relatively recent process in metal forming metallurgy, where parts are obtained from the powder constituents. The basic processes in PM are: powder production through grinding, then mixing, compaction and sintering, and sometimes a fifth stage is necessary, such as rectification. In PM, the powders, once mixed, are compacted in dies where the referred powders take on the shape of the cavity of the die. In the sequence, they are placed into sintering furnaces where they acquire consistency and mechanical resistance [7, 8].
Microencapsulated Materials: Soft Magnetic Composites, or simply SMCs, are basically ferromagnetic powder particles, coated with an electrical insulating film, such as polymers and oxides. SMC components are manufactured using traditional powder metallurgy techniques. The production process for these components, in general terms, comprises compaction and subsequent thermal treatment for curing the resin or consolidation [9].

Powder Injection Molding (PIM): PIM is an alternative process of P/M that combines the P/M with the injection. The process is based on a mixture of powders (such as metallic and ceramic powders) with a binder (basically waxes and polymers). Next, the mixture is injected into a mold, acquiring the shape of the cavity. Eventually to this molding process, it is performed the removal of the binder by solvent application. Finally, the complete extraction of the polymer takes place by heating and subsequent sintering processes. As result, metallic or ceramic pieces are obtained with high precision and complex geometry [10].

The magnetic and electrical properties of the materials obtained by P/M are influenced by several factors, such as the formation of alloys, presence of porosity and surface oxidation of the powder particles, particle size of the powders, crystalline lattice of the grain size and presence of impurities. Some of these features are positive in contrast to others, that are negative with respect to the magnetic and electrical properties and the use of these materials in cores of electrical machines [11-14].

The sintered materials most commonly used in electromagnetic device cores, such as rotating electrical machines, are pure iron, iron-cobalt, iron-phosphorus, iron-silicon, iron-phosphorus-silicon, iron-nickel alloys and ferritic steels [15-17].

2.2. Physical Properties of Interest of Materials for Cores of Electrical Machines

The physical properties of interest for use of a particular material and process in cores of rotating electrical machines or electric motors are: magnetic properties (coercivity, permeability, saturation induction); electrical resistivity; and mechanical properties (hardness and compression curves / yield stress).

Regarding the magnetic properties, the materials to be used in cores of electrical machines must have: high magnetic permeability, which reduces the reluctance of the magnetic circuit of iron cores, concentrating the entire magnetic field in the air gap; high saturation induction, which enables to work with higher magnetic flux, resulting in greater torque on the shaft; and low coercivity, which reduces the hysteresis loss cycle [1, 2].

Concerning the electrical resistivity, this parameter must have the highest possible value in order to minimize the effect of eddy currents. Whenever there is the incidence of an alternating flux on a magnetic core, there will be induced currents (eddy currents or Foucault currents) on the core. The stator and rotor are constructed with laminated and insulated sheets, since this isolation between sheets restricts the induced currents to a smaller area of circulation. The eddy current losses in a solid core are significantly larger than those in the cores made from electrically isolated sheets. The smaller the sheet thickness, the smaller the eddy currents and power losses in these cores. The reduction of induced currents may also be obtained from an increase in the electrical resistance of the part or from the increased electrical resistivity of the material, since resistance (or resistivity) and electrical current are inversely proportional physical quantities. For this reason, high-performance electric machines are built with a silicon steel sheet, which has higher electrical resistivity than the low carbon steel [1, 2].

With respect to mechanical properties, materials that can be used in cores of electrical machines must withstand the stresses caused by the resistive load torque and vibration, among others. Thus, hardness or ductility tests and compression curve versus deformation or flow curve should be performed as well as evaluation of the microstructure of the materials.

In summary, the material used in the construction of the stator and rotor cores must have the following properties:

- high permeability magnetic;
- low magnetic coercivity;
- high electrical resistivity;
- high saturation induction; and
- hardness or ductility features compatible with the vibrations in which the machine is subjected.

2.3. Synchronous Machines with Permanent Magnets

Rotating electrical machines with three-phase power, usually, can function as a motor or generator. As motors, it converts an electric power from a source in a mechanical power that trigger a load coupled on the shaft. As generating, the opposite occurs [1, 2, 5]. For this reason, the electric motors may be called simply as rotating electrical machinery or electrical machines.

Three-phase rotating machines can be synchronous or asynchronous. In synchronous motors the angular velocity of the shaft is constant and independent of the load coupled to the shaft, ie up to certain values of power, with the use limit, the nominal power of the machine. In asynchronous motors, there is a drop in the angular velocity when load is coupled to the shaft [1, 2, 5].

Regarding the constructive aspect, the three-phase machines consist mainly of two parts [1, 2, 5]:

- stator: fixed part of the machine constructed of laminated steel sheets in which the armature windings are placed with three phase supply, lagged 120^o. The windings are arranged spatially in a such way that the currents of all phases contribute positively to the generation of a wave of the rotating magnetic flux or rotating field.
- rotor: rotating machine part also constructed of rolled steel sheet in which the field windings are placed.

Synchronous machines with permanent magnets are rotating three-phase machines in which the rotor windings, usually supplied with direct current, are replaced by permanent magnets of high energy product such as NdFeB. In general, these machines have high yield (greater than 90%) and, in some applications, such as servomotors, are used as servomotors, operating at high speeds and high frequency of armature currents [1, 2, 18].

2.4. Simulation by Finite Elements Software

The results of the electromagnetic iterations of a rotating electrical machine can be obtained through simulations using the finite element software FEMM 4.2 (Finite Element Method Magnetics). The finite element method aims at solving differential equations for a variety of inputs. The main objective is to divide the problem into a number of regions with a simple geometry (eg triangle). In each element, the solution is approximated by an interpolation of the values of each vertex of the triangle [19].

By means of FEMM 4.2, it is possible to check important data such as the momentary torque of the electrical machine, the flux linkage in each coil and losses due to eddy current. The knowledge of these results allows the designer to check the efficiency of the machine and the properties that must be worked to achieve the optimum working point.

3. Material and Methods

Initially, specimens were obtained, where it was used phosphorous (1, 2 and 3%), silicon (1, 3 and 5%) and nickel (50%), mixed with pure iron, compacted and sintered. In the sequence, some physical properties such as saturation induction, magnetic permeability and coercivity, electrical resistivity, magnetic loss *versus* frequency, hardness and yield stress were evaluated. Finally, applying the finite element software FEMM 4.2, it was performed the simulation of a synchronous electrical machine with permanent magnets, using three different topologies of the rotor, in which it was compared the magnetic flux density of air gap and the torque generated by each rotor type.

3.1. Specimens

The definition of the alloy to be used in rotor and stator cores of the machine was based on a study of the physical properties of some sintered alloys such as FeP, FeNi and FeSi and their variations. In order to analyze the magnetic properties and electrical resistivity, it was used the die of Figure 1a, where specimens were obtained in the form of rings (Figure 1b).

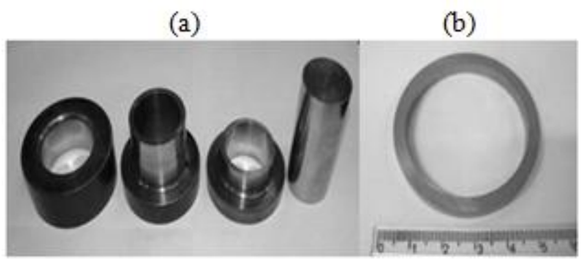


Fig.1 - Samples in the form of ring - (a) Die - (b) Specimen. (scale in centimeters).

In turn, analysis of the hardness and yield stress of the studied alloys was made concerning the use of the die shown in Figure 2a, where specimens were obtained in the shape of a cylinder (Figure 2b).

Fig. 2 - Samples in the form of cylinder - (a) Die - (b) Specimen.

The study was conducted from sintered alloy, obtained from iron powders mixed with phosphorus, silicon and nickel, as mentioned before, acquired from Hoganas Brazil Ltda. According to the manufacturer's certificate, the iron powder used was ASC100.29, with 99.4% particle size between 45 μm and 150 μm. The Fe_3P powder (84% Fe, 16% P) has 90% of its size below 14.58 μm. The powder FeSi 45 (55% Fe and 45% Si) has 87% of its content between 45 μm and 250 μm and the nickel powder has a minimum particle size of 3 μm and a maximum of 7 μm. The iron powder was mixed with phosphorous (1, 2 and 3%), silicon (1, 3 and 5%) and nickel (50%) in a double cone mixer with rotation of 60 rpm for 20 minutes for dispersion of the constituents. It was also added to the mixtures 1% of solid lubricant (zinc stearate).

Regarding the compaction pressure, the samples were subjected to an average pressure of 600 MPa, followed by the literature guidance [7, 8].

Sintering of the specimens was carried out in a tubular muffle furnace with controlled atmosphere (atmospheric pressure) and green gas (5% hydrogen and 95% nitrogen). It was used a heating rate of 10 ^{o}C per minute, from room temperature until 500 °C, remaining the parts at this temperature for 30 minutes to remove the solid lubricant (zinc stearate). In the sequence, the temperature was increased to 1.150 °C, occurring then the sintering, with a new isothermal level at this temperature for 60 minutes [7, 9]. Finally, the parts remained in the furnace for slow cooling to room temperature.

3.2. Obtaining the physical properties

The magnetic properties were obtained from the magnetic curves (hysteresis and magnetization) that correlate the magnetic field (H) applied to a material with the resulting magnetic induction (B). From the hysteresis loop, it was obtained retentivity (remanent magnetism) and coercivity (demagnetizing field). Through analysis of the magnetization curve, it was obtained magnetic permeability and saturation induction, or maximal induction (which can also be viewed from the hysteresis loop) [20]. The determination of the basic magnetic properties of the materials in the form of a ring (toroid) follows the norm ASTM A773 [21]. The magnetic curves were obtained from a TLMP-HCT-14 model device.

For the application of this analysis method, the sample preparation is required, which consists in the coiling (winding of copper wires) of primary and secondary coils in the ring, known as the Rowland ring (Figure 3). The procedure consists of isolating the ring with plastic wrap to prevent the stripping of the enameled wire (Figure 3-a), winding of secondary coils (Figure 3-b) and new insulation (Figure 3-c) followed of the winding of the primary coils (Figure 3-d).

(a) (b) (c) (d)

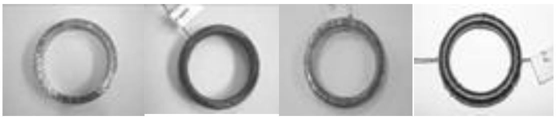


Fig. 3 Sample preparation steps: (a) isolating (b) secondary winding, (c) isolating and (d) the primary winding

The electrical resistivity of the material (specimens) of the alloys was determined by calculating the electrical resistance. For this measurement, it was used a device called multimeter, which directly measures the electrical resistance of the body. However, for very low electrical resistance measurement, one applies a tension in the specimen and the electrical current is then measured. Therefore, the sample for the determination of the resistivity should be in the form of a thin and long bar. One method is the use of a ring, by cutting a segment of it, making this the shape of a curved bar, ie great length and small cross-sectional area. Ohm's Law states that [22]:

$$R = \frac{V}{I} \Rightarrow \rho = R\frac{A}{l} = \frac{V}{I}.\frac{A}{l} \quad [1]$$

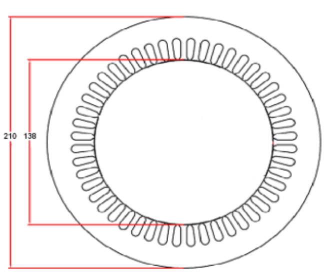
where ρ is the electrical resistivity [μΩ.m]; R, the electrical resistance [Ω]; V, the applied voltage [V]; I the electric current applied [A]; A, the cross sectional area of the bar [m^2] and l represents the length of the bar (or segment of a ring) [m].

Fig.4 – Segmented ring for measuring electrical resistivity.

To evaluate the vibration resistance of a material to be used in a rotating electrical machine, it was also carried out mechanical tests on specimens. Hardness tests (HB) were performed in England Precision durometer with indenter of 2.5 mm of sphere and 187.5 kgf load according to norm ASTM E10 [23]. Compression tests were conducted on a universal testing machine EMIC DL20000, using a speed of 2.0 mm/min in accordance with norm ASTM E9 [24].

3.3. Procedures for Machine Simulation

The synchronous machine studied in this work was assembled on the basis of an induction motor with high performance, produced by Voges Motors. The data of the machine and stator sheets are shown in Figure 5.



Motor 10 CV 220 v 60 Hz
Number of poles: 4
Disc outer diameter: 210 mm
Inner disc diameter: 138 mm
Number of slots: 48
Internal diameter : 138 mm
Sheet metal package: 148 mm
Number of plates: 320

Fig. 5 – Schematic of machine stator sheets.

The three rotors with four poles (Figure 6) were designed based on the concepts of synchronous electrical machines with permanent magnets of Nd-Fe-B [1, 2, 5, 6].

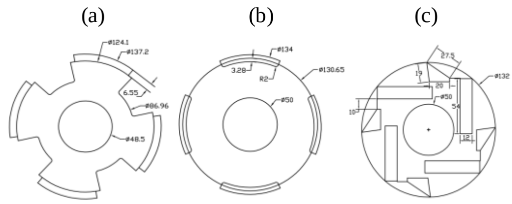


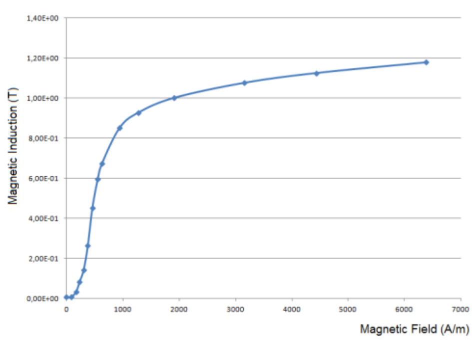
Fig. 6 – Topology of rotors studied - (a) salient poles with magnets on the surface of the saliences - (b) straight poles with magnets on the rotor surface - (c) embedded magnets within the rotor.

For the simulation of the proposed machines, it has been inserted on FEMM 4.2 software the stator topologies (Figure 5) and the rotors (Figure 6), winding characteristics and magnetization curves of materials of the rotor cores (Figure 7). Simulations were performed for the stator core with M15 sheets, but with variations in the rotor material, that is, from rotor sheets M15 and rotors from the sintered alloys studied. The nominal current was 14.2 A per phase and 192 conductors in series per phase. The 2% Fe-P alloy was the sintered material that presented suitable magnetic and electrical properties and, because of that, the simulations showed in this work were based on the referred alloy.

4. Results and Discussion

4.1. Physical Properties Obtained of the Sintered Alloys

Magnetic properties were obtained (from BXH curves), resistivity (from equation 1) and mechanical properties for the studied specimens. Figure 7 shows the magnetization curves of sintered pure and Figure 8 shows hysteresis loop of sintered pure iron.



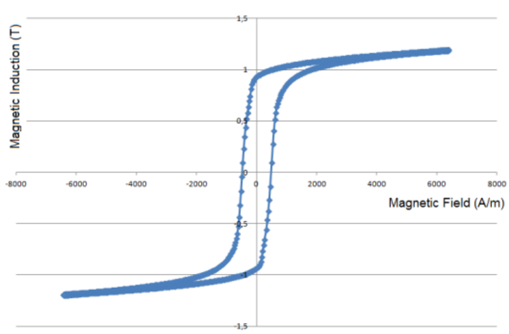


Fig. 7 – Magnetization Curve sintered pure iron.

Fig. 8 – Hysteresis loop of sintered pure iron.

From table 1, it can be seen that the Fe-50% Ni has lower coercivity and hysteresis losses than the other sintered materials. However, this alloy also presents lower saturation induction, a property of great importance for the application of these materials in cores of electrical machines [25,26]. It should be noted that the hysteresis curve of pure Fe has similar characteristics to the low carbon iron, a typical material used in packs of laminated steel sheet employed in the construction of cores of conventional rotating electrical

machines [1, 2, 5]. The Fe-1% P showed higher maximal induction, lower hysteresis loss and coercivity if compared to pure iron.
Table 1 shows the results of the density, electrical resistivity, magnetic and mechanical properties observed in a ring and cylinder form, from average values of three specimens for each material.

Table 1 – Physical properties of the sintered alloys studied

Material	ρ_m [g/cm^3]	ρ_e [$\mu\Omega$.m]	B_r [T]	H_c [A/m]	B_{max} [T]	μ_r	HB	σ_ε [kgf/mm^2]
Pure iron	6.632	0.157	0.9	448.2	1.19	1,852.60	52.1	13.99
Fe-1%P	6.712	0.197	1.0	215.8	1.25	2,766.10	125.0	14.79
Fe-2%P	6.874	0.358	1.0	207.9	1.36	4.198.70	202.0	12.64
Fe-3%P	7.003	0.421	0.5	210.7	0.98	919.4	243.0	11.99
Fe-1%Si	6.697	0.276	0.7	246.3	1.03	1,959.80	64.5	14.93
Fe-3%Si	6.732	0.444	0.5	225.4	0.85	1,258.70	73.2	15.99
Fe-5%Si	6.762	0.482	0.3	216.3	0.67	493.8	102.0	17.24
Fe-50%N	7.251	0.371	0.2	112.1	0.93	945.6	101.0	16.49

In the referred table, ρ_m is the density; ρ_e, electrical resistivity; B_r, retentivity; H_c, coercivity; B_{max}, saturation induction; μ_r, relative magnetic permeability; *HB*, hardness in Brinell scale and σ_e is the yield stress.
The sintered pure iron has a density between 6.8 and 7.4 g/cm^3; the Fe-1% P shows a density between 7.0 and 7.4 g/cm^3; Fe-3% Si presents a density between 6.8 and 7.2 g/cm^3, and Fe-50% Ni has a density between 6.8 to 7.5 g/cm^3. However, only the 50% Ni-Fe alloy resulted in a density according to the references (7.25 g/cm^3) [3]. The densities of other alloys present values at the lower limit of the cited range or below this limit. This can be attributed to many variations in the processes of P/M, in which factors such as particle size and shape, compaction pressure, sintering levels and atmosphere influence the desired density [7, 8].
In addition, some references do not indicate the compaction pressure used for soft magnetic materials by P/M, and in some studies, it is employed pressures up to 800 MPa for composite materials by P/M [27], and such pressure tends to increase the density of the specimens.
With respect to resistivity, this parameter increases with additions of P, Si and Ni to pure Fe, since these additions distort the crystal lattice [28, 29]. Pure Fe presented resistivity of 0.157 μΩ.m against 0.482 μΩ.m related to Fe-5%Si alloy. The higher resistivity was obtained for Fe-5%Si alloy, once the silicon, during the sintering process, does not densify homogeneously into the iron and the replacement of the ferrite grains by silicon increases the imperfections in the crystal lattice, leading to the increment of the resistivity [30-33]. The high resistivity presented in the tests with a soft magnetic material is essential for use in cores of rotating electrical machines, since, in this way, it reduces eddy currents. The reduction of the induced current can be interpreted as an increase in electrical resistance of the samples, since they are physical quantities inversely related. The reduction effect of the induced currents can also be obtained by increasing the electrical resistivity of the material. Therefore, the higher the resistivity of the material, the smaller the induced currents and losses due to eddy currents [34].
The addition of phosphorus allows obtaining the desired mechanical properties, using lower sintering temperatures, due to formation of a transient liquid phase. The phosphorus in

percentage less than 1% does not give the sintered iron decrease in yield strength. Moreover, the presence of the referred element promotes the increase of hardness [28, 35]. In fact, any increase in the content of an alloying element in a metal, such as iron, increases the hardness of the alloy due to distortions in the crystal lattice [36, 37].

Regarding the studied alloys, the Fe-3% P alloy showed yield strength of 120.0 MPa, while Fe-5% Si, 172.4 MPa. The 1008 steel used in most of the cores of rotating electrical machines [1, 2] has an average yield strength of 170 MPa, a value close to the studied alloys. The AISI 1008 steel has a hardness value of 86 HB [38]. The hardness of the sintered pure Fe was 52.5 HB, and Fe-3%P showed a hardness value of 242.9 HB. Thus, with respect to mechanical properties, the sintered materials studied are within acceptable parameters for use in the construction of cores of most rotating electric machines [1, 2].

4.2. Simulation Results

Figure 9 shows the amplitude in module of the air-gap induction and Figure 10 depicts the lines of magnetic flux generated in the longitudinal plane of the machine for rotor configuration of the salient poles and M15 steel sheets in the rotor. In turn, Figures 11 and 12 present the same data for rotor with sintered Fe-2%P alloy.

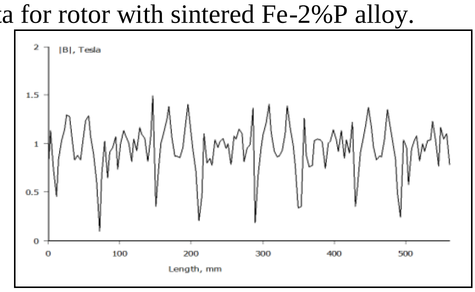


Fig. 9 - Machine simulation with rotor of salient poles from M15 steel sheet - Air-gap flux density.

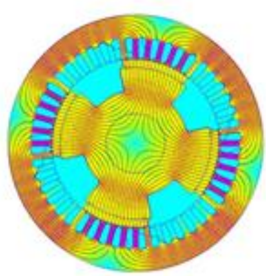


Fig. 10 - Machine simulation with rotor of salient poles from M15 steel sheet - Flux lines in the longitudinal plane of the machine.

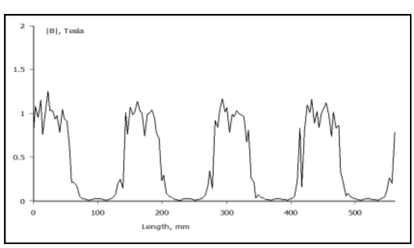


Fig. 11 - Machine simulation with rotor of salient poles from Fe-2%P sintered - Air-gap flux density.

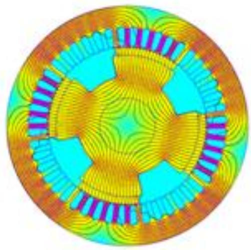


Fig. 12 - Machine simulation with rotor of salient poles from Fe-2%P sintered - Flux lines in the longitudinal plane of the machine.

Figure 13 shows the amplitude in module of the air-gap induction and Figure 14 presents the lines of magnetic flux generated in the longitudinal plane of the machine for rotor configuration of the straight poles and M15 steel sheets in the rotor. Figures 15 and 16 show the same data for rotor with sintered Fe-2%P.

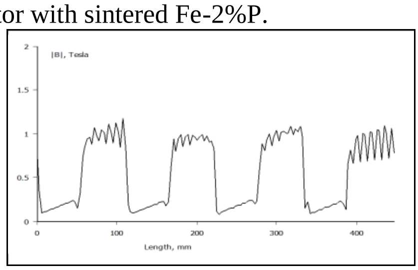


Fig.13 – Machine simulation with rotor of straight poles from M15 steel sheet - Air-gap flux density.

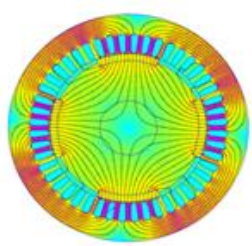


Fig.14 – Machine simulation with rotor of straight poles from M15 steel sheet - Flux lines in the longitudinal plane of the machine.

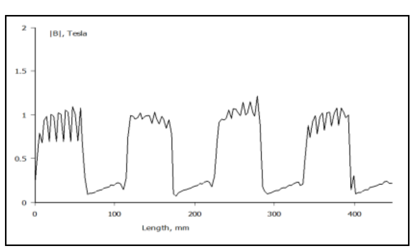


Fig.15 – Machine simulation with rotor of straight poles from Fe-2%P sintered - Air-gap flux density.

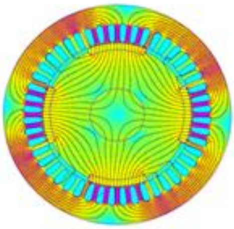


Fig.16 – Machine simulation with rotor of straight poles from Fe-2%P sintered - Flux lines in the longitudinal plane of the machine.

Finally, Figure 17 shows the amplitude in module of the air-gap induction and Figure 18 depicts the lines of magnetic flux generated in the longitudinal plane of the machine for the configuration with embedded magnets and M15 steel sheets in the rotor, while Figures 19 and 20 show the same data for rotor with sintered Fe-2%P.

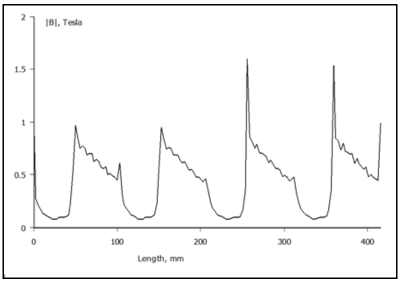


Fig. 17 - Machine simulation with rotor of embedded magnets from M15 steel sheet - Air-gap flux density.

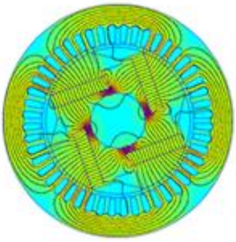


Fig. 18 - Machine simulation with rotor of embedded magnets from M15 steel sheet - Flux lines in the longitudinal plane of the machine.

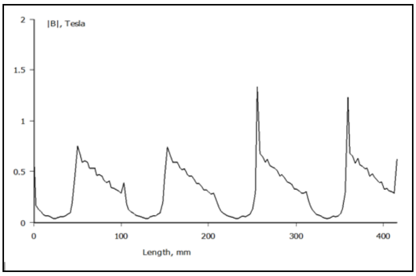


Fig. 19 – Machine simulation with rotor of embedded magnets from sintered Fe-2%P alloy - Air-gap flux density.

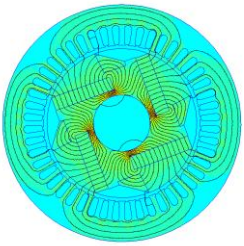


Fig. 20 - Machine simulation with rotor of embedded magnets from sintered Fe-2%P alloy - Flux lines in the longitudinal plane of the machine

Table 2 shows the maximum values of air gap flux density and torque developed on the shaft, considering the machine functioning as motor.

Table 2. Air gap flux density and torque

Rotor Torque	Torque [N.m] M15	Torque [N.m] Fe- 2%P	Flux Density [T] M15	Flux Density [T] Fe- 2%P
Salient Poles	34.92	34.80	1.22	1.25
Straight Poles	33.65	33.61	1.17	1.21
Embedded Magnets	22.68	19.53	1.67	1.35

In the simulations performed statically, the instantaneous torque and the magnetic flux in the core of Fe-2% P alloy for both topologies (salient poles and straight poles) resulted in values close to those related to traditional laminated steel sheets. The equivalence among the results is probably due to high values of magnetic permeability, saturation induction and resistivity, as well as low coercivity displayed in electric and magnetic tests [39]. In a rotating electrical machine working as a motor or generator, the torque on the shaft is a function of the magnetic flux air gap (maximal induction) and the inclination of the magnetic flux lines in the air gap, also known as load angle for the case of rotating synchronous electric machines. A rotating electrical machine is, therefore, a dynamic transducer energy, ie as motor, it transforms electrical energy from the armature windings into mechanical energy delivered to a load on the shaft. In a generator, the opposite takes place, i.e. it transforms mechanical power on the shaft from a turbine, for example, into electrical energy. In both cases, the conversion of mechanical energy to electrical and vice versa occurs from the magnetic field, and the magnetic flux of air gap (or maximum induction) is the determining factor. As a result, through simulation, it is regarded as better results the machines that operate with higher magnetic flux gap and the greatest final torques [1, 2, 5].

It is important to emphasize that the hysteresis curves were plotted at low frequencies, or nearly DC level. It should be also noted that the simulation of torque results in instantaneous values for a given relative position between the alignment of the rotor and stator cores, without considering the rotation frequency of the rotor or the frequency of the electrical current that supplies the armature windings. It is observed that, while the losses in sheets cores remain constant with increasing frequency, the losses in the cores of soft magnetic materials decay exponentially until the 400 Hz [4]. This important feature of sintered cores allows its use in certain types of rotating electrical machines such as high

speed motors, servo motors that are drived by electrical currents with frequencies nearly or higher than 400 Hz, and generators with high numbers of poles.
Thus, the proposed machine in this study with rotor and stator cores of sintered materials, when supplyed with armature current with frequency of 60 Hz, has a very low yield. However the yield would increase exponentially to higher frequencies. The effect of the construction of the laminated core plates does not reduce the eddy currents if compared to the solid core. There is an increase of the induced voltage while the magnetizing current decreases. However, the Foucault currents increase [4, 40]. An alternative to this machine operating at low frequencies of armature current would be the construction of the rotor with sintered material and the stator with core sheets. The use of topology with embedded magnets in the rotor core increases the concentration of magnetic flux, aiding in the overall efficiency of this hybrid machine. Such combination would be very interesting, because the significant flux variation occurs in the stator, while in the rotor the flux remains substantially constant.

5. Conclusions

Regarding the density, mechanical properties, electrical resistivity and magnetic properties, the studied alloys showed characteristics that can be also found in the literature. Thus, the alloys obtained in this work present the minimum requirements to be applied in some parts of rotating electrical machines.
Tests and simulations performed with soft magnetic material demonstrated promising results if compared to machines built from conventional method of laminated sheets. The magnetic flux in the core of Fe-2%P showed equivalent results, mainly related to the magnetic flux, where there was a small increase of this parameter with respect to the traditional laminated steel sheets, although there was a reduction in the final torque of the electrical machine, considering the same excitation power. This problem can be solved especially in applications that have input power with possibility of variation of the applied voltage, leading to an increase of the magnetic flux as well as keeping the torque at similar levels concerning the traditional machine models with laminated sheets.

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