Design of Electromagnetic Devices with Soft Magnetic Composites

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***Abstract* - The Iron-Resin composites are new soft magnetic materials produced by powder metallurgy process. An efficient use of this new technology of magnetic material needs a new structural design approach taking account of the advantages and constraints of the material, because the direct replacement approach is usually not optimal. Specific structures of electromagnetic devices are presented which were developed for an optimal use of the Soft Magnetic Composites. The research is illustrated by original realizations of electromagnetic devices in several domains of application: transformers, inductors, brushless motors, brush DC and AC motors.**

I. INTRODUCTION

With the continuous developments in powder metallurgy materials and processes, new soft magnetic materials are now commercially available for AC magnetic applications. These soft magnetic composites (SMC) are made of ferromagnetic particles separated by a dielectric material. These materials, often referred as dielectromagnetics, generally present relative low values of permeability but they also possess a lot of advantages which can be very interesting for a lot of electromagnetic devices, if they are properly used during the design process. The technology associated to powder metallurgy permits the reduction of production steps and cost.

II. CHARACTERISTICS OF SOFT MAGNETIC COMPOSITES

The soft magnetic composites (SMC) are dielectromagnetic powder materials in which ferromagnetic particles are insulated from each other by a dielectric thermoset resin [1]. Complex shapes of magnetic circuits can be produced with this material by conventional powder metallurgy process. The typical properties of the Soft Magnetic Material ATOMET EM-1, manufactured by Quebec Metal Powders Ltd., are presented in Table 1. One can notice some interesting features of this material for the design of electromagnetic devices:

- the mechanical strength is adequate for usual applications.
- the value of electrical resistivity is rather high because the iron particles are isolated by the resin. The eddy current losses are then minimized in the parts of the magnetic circuit where the flux is varying at a relatively high frequency.
- the thermal conductivity is similar to the conductivity of conventional laminated materials in the plane of laminations. But this thermal property is isotropic [5] and the heat transfer from the device to the ambiance is maximized, because the total external surface of the device can be used for the dissipation.
- the magnetic, electric and thermal properties of the iron-resin composites are isotropic. This important feature can be used to design new optimized structures of electromagnetic devices where the magnetic and heat flux flow in three dimensions [5].
- the magnetic losses are similar to the losses of low grade laminations at 60 Hz but they are much lower in the composite material as the frequency increases, because the Eddy current losses are minimized by the isolation between particles [14].

The Soft Magnetic Composites present lower values of permeability than conventional laminated material. This disadvantage is minimized in magnetic circuits including permanent magnets where the length of the intrinsic distributed air gap of the Soft Magnetic Composites is much lower than the length of the total air gap of the device. In other applications, the device structure can be adapted by an optimal use of the isotropic magnetic properties [5].

TABLE I
Properties of ATOMET EM-1 pressed at 620 MPa/65 C and cured in air at 200 C for one hour.

Density	*kg/m³*	7.20
Strength *MPIF Stand. 41*	*MPa*	110 - 125
Thermal conductivity	W/K-m	20
Electrical resistivity	*µohm-m*	150 -200
B_{max}	*T*	1.5
μ_{max}	---	290
B_r	*T*	0.25
H_c	*A/m*	420
Magnetic losses (.5T)	*W/kg*	
60Hz	400Hz	1000Hz
3.7	26.5	70

III. DESIGN OF ELECTROMAGNETIC DEVICES WITH SMC

A. *Use of soft magnetic materials in electromagnetic devices*

The optimal use of a soft magnetic material for the design of electromagnetic devices is issued from a compromise between its magnetic, thermal, mechanical properties, and the cost of the production and assembly process. The characteristics of a new material are not necessarily better than the characteristics of a conventional material in all these fields. The "direct replacement" technique, where the new material is used without any structural or dimensional modification in a device, which was optimized for a conventional material, is generally not interesting in terms of efficiency or power to weight ratio. The systematic research of new topological structures and the adoption of new compromises between the material properties and the specifications of the application is the best approach to get an optimal use in terms of technical and economical performance. This global optimization approach has been successfully adopted by the authors in a wide range of SMC applications [15].

B. Optimal use of soft magnetic materials in electromagnetic devices

The Soft Magnetic Composites (SMC) present a lot of interesting characteristics which can improve the performance of electromagnetic devices, if they are properly used during the design process. With this technology, the number of production steps can be reduced and an integrated process of production can drastically decrease the cost price. The magnetic circuit can be pressed in a single operation or assembled from several pre-pressed parts, by use of mechanical or isostatic pressing methods. In the future, new techniques like Dynamic Magnetic Compaction (DMC) will also permit to press together in a single operation several parts made of different materials (magnets and yoke, yoke and windings). With DMC, the levels of compaction pressure will improve the density and permeability of the SMC parts, by elimination of the internal volume of air. It is also possible to design high performance magnetic structures with complex shapes, which are too difficult or too expensive to realize with laminated sheet steels.

The device structures must be adapted to the specific advantages of the SMC characteristics to find efficient and optimal solutions.

1) Optimal use of isotropic magnetic properties: One of the most important advantage of the Soft Magnetic Composites is the isotropy of their magnetic and thermal properties.

In transformers, inductors and electromagnets, the magnetic isotropy can be used to design new magnetic structures with high power to weight ratio, where the flux flows in three dimensions.

In the stator yoke of brushless PM motors or in the armature of brush DC or AC motors, a portion of the magnetic flux can also circulate in the axial direction. For these reasons, it is possible to expand the tooth tips in the axial direction, and thus to maximize the axial length of the active air-gap area for a given total axial length of the motor fixed by the specifications. In such structures, the air-gap flux is concentrated into the center part of the rotor teeth under the coils and the yoke. Because the axial length of the center part of the rotor teeth under the coils and the axial length of the yoke is smaller than the axial length of the tooth tips, the end-windings are now axially inserted and the total axial length of the motor is reduced (cf Fig. 1).

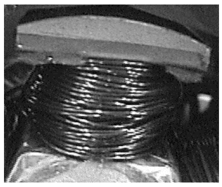


Fig. 1. View of a single tooth with axially inserted end-windings

In brush DC motors, the commutator and the brushes can also be axially inserted to minimize the total axial length. With this method, the isotropic properties of the soft magnetic composites are used to minimize the axial length of a motor without reducing the torque performance. This kind of improvement is very interesting in automotive applications like the electric fans.

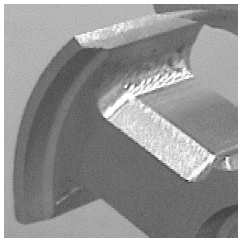


Fig. 2. Detailed view of a single tooth using the isotropic magnetic properties of the Soft Magnetic Composites

When an isotropic soft magnetic composite is used, the cross-section profile of the center part of the rotor and stator teeth under the coils can be made round, oval, or circular to maximize the copper filling factor (cf Fig. 2). The heat transfer between the conductors and the yoke can be maximized and the power to weight ratio is improved.

2) Optimal use of isotropic thermal properties: The heat dissipation of electromagnetic devices made of SMC is more efficient than in the case of laminated materials because their thermal conductivity is isotropic : the whole external surface of the device can be used for dissipation. In specific device structures, cooling devices like fins or water tubes can be directly integrated in the magnetic circuit without increasing the weight.

3) Low magnetic losses at high frequency: In Permanent-Magnet motors, the size and weight of the yokes can be reduced, if the number of poles is increased. When the speed of the motor is imposed by the specifications, the frequency of the supply currents must be proportionally increased. The stator yoke is then excited at a relatively high frequency (up to 1 kHz) and the magnetic losses are increasing. Because the Soft Magnetic Composites have low magnetic losses in this frequency range, it is possible with such materials to design motors with a high number of poles to improve the torque to weight ratio.

With conventional laminated materials, it is often necessary to oversize the weight of filtering inductors used in applications with an important harmonic content to take account of the important Eddy current losses. The SMC inductors are well adapted to this kind of specifications in terms of energy to weight ratio.

4) Vibrations and audible noise: The vibrations and the noise of the electromagnetic devices can also be reduced by the use of Soft Magnetic Composites, because the stack of laminations has been replaced by a solid and homegeneous yoke [12].

5) Influence of the low permeability of SMC: In the case of magnetic circuits with Permanent-Magnet, the relatively low values of unsaturated permeability of the Soft Magnetic Composites have a minor influence on the performance. In Permanent Magnet motors for example, the effective air gap of the magnetic structure is imposed by the length of the magnet which has a relative permeability equal to unity. It has been showed that direct replacement of the laminated material by Soft Magnetic Composites in the stator yoke of a permanent magnet motor decreases the maximum available torque by only 8% even if the permeability of the dielectromagnetic material is 70% lower [1].

In other motor applications, the device structure can be adapted by using isotropic magnetic properties in order to maximize the air gap area in a given axial total axial length fixed by the application specifications. The reduction of magnetizing inductance imposed by the low permeability is then compensated by the higher air gap area. In the case of voltage fed devices, the no-load current is then limited.

From the experience of the authors, the optimal and efficient use of SMC in the design of electromagnetic devices needs an extended research of new topological structures. On the other hand, specific CAD tools and methods based on a global optimization approach including the coupling of magnetic, electrical, thermal and mechanical models must be developed, because expert data are not available in the case of this new material technology.

IV. Realizations

A. Transformers

The relatively low values of unsaturated permeability of SMC seems at first sight to be an important drawback for an efficient use of this material in transformers. The magnetizing current will be higher than in the case of conventional materials with high permeability. A “direct replacement” of laminated materials by SMC in a conventional structure of core (E and I shape) is not suitable. Because the magnetic and thermal properties of SMC are isotropic, their overall thermal properties are better than the laminated magnetic materials [4]. All core structures presenting a cylindrical symmetry around one revolution axis are adapted for an optimal use of the isotropic magnetic and thermal properties of SMC [12]. One of the simplest structure presenting this topological property is presented in Fig.3: one can notice that the windings are totally enclosed in the magnetic core (see Fig. 5). The external surface of the core is used to dissipate the heat generated by the copper losses in the internal windings and the magnetic losses in the magnetic material. The transformer can be associated to a heat-sink or its core can be directly equipped with integrated cooling fins made of the SMC material itself on the external surface of dissipation. These fins are pressed directly with the core in a single operation and if they are adequately oriented, the magnetic flux can also circulate in them: the cooling fins are then “magnetically active” and the power to weight ratio of the transformer is increased (cf Fig.4). [12].

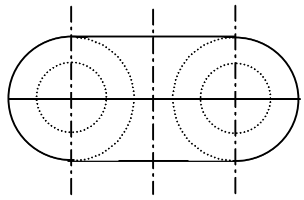


Fig. 3. Sectional view of a transformer structure presenting a cylindrical symmetry around one revolution axis

In such structures, EMI is minimized because the windings are totally enclosed and shielded by the magnetic circuit. The audible noise is also reduced because the vibrations are avoided by the internal structure of the SMC material.

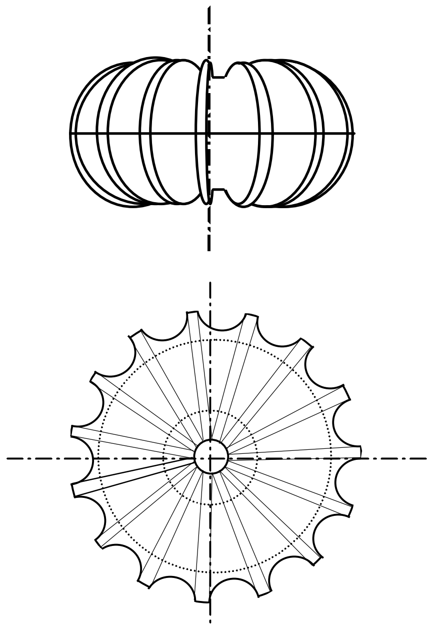


Fig. 4. Side and upper views of a SMC transformer presenting a cylindrical symmetry and equipped with “magnetically active” fins

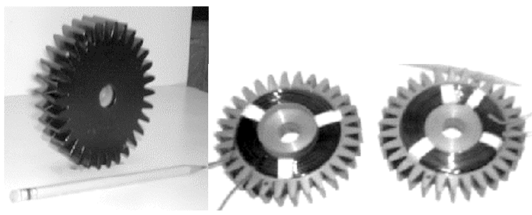


Fig. 5. 60Hz Single phase SMC transformer 120V/12V, 100VA presenting a cylindrical symmetry and equipped with “magnetically active” fins

B. Inductors

The low relative permeability of SMC is not a drawback for the design of inductors. The Soft Magnetic Composites are well adapted to inductors with a high current harmonic content (harmonic filters, smoothing inductors) because they don't have Eddy current losses. The structures presenting a cylindrical symmetry and "magnetically active" fins are optimal solutions for these applications. It is easy to distribute small air gaps along the device height to minimize the additional copper losses induced by the proximity effect. Fig. 6 presents a SMC filtering inductors. [12].

SMC electromagnetic lamp ballasts using similar structures have been designed and successfully tested.

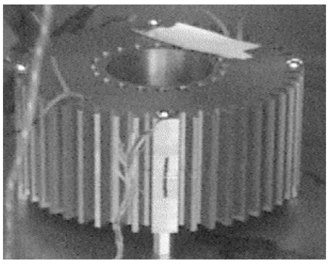


Fig. 6. 1kHz SMC Filtering inductor with "magnetically active" fins

C. Brush DC and AC motors

Specific structures of brush motors armatures have been determined for an optimal use of SMC. The authors have shown that the concentrated winding structures are very well adapted to the realization of armatures of brush DC and AC motors with Soft Magnetic Composites [11] [3] [6]. With this kind of windings, it is possible to avoid the interlocking of the coils: the armature simple coils are directly wound around each tooth of the rotor magnetic circuit. This solution eliminates the problem of the interlocking of the coils and the problem of the circulating currents. All the path voltages are perfectly balanced and the current commutation is improved when compared to the classical structures. The use of a concentrated is reducing the copper volume of the end-winding, the copper losses and the total axial length of the motor. The efficiency is improved when compared to the efficiency of classical structures [1] [6] [3]. A concentrated winding structure is easier to realize than a lap winding or a wave winding. The rotor structures with a concentrated winding have a small number of slots and the magnetic circuit is easier to realize. With a small number of slots which are relatively large, the mechanical constraints on the direct molding process of the rotor SMC yoke are reduced. It is also possible to easily insert the end-windings in the active part of the rotor magnetic circuit by use of the SMC isotropic properties: this axial insertion of the end-windings improves the reduction of the volume of copper and the total axial length of the motor. The low relative permeability of SMC is also reducing the value of the coil inductances in the armature and the commutation process in both collector and armature is improved. In the case of Permanent-Magnet motors, this low value of permeability has a negligible influence on the torque to current ratio.

The concentrated winding technique is too often associated and restricted to windings with a short pitch, i.e. windings with lower performances than the performances of the classical winding structures, in terms of torque to current ratio. The concentrated windings with a short pitch are then limited to sub-fractional power applications (lower than 100 W) like electrical motors used in computer peripherals or toys.

The proposed structures with concentrated windings are also realized with several concentric coils which are wound around the same rotor tooth. The number of commutator segments must be higher than the number of rotor slots [3]. This kind of solution reduces the number of turns per coil for a same value of the DC voltage supply and a same speed range of the motor. The inductance value of each simple coil is reduced and consequently the commutation problems are minimized when compared to the case of a concentrated winding with only one coil wound around each tooth. It is also possible to arrange connections of the leads of each coil to the commutator segments to obtain balanced emf in the different coil paths between brushes. These structures can be used for motors on a large range of power and their cost of realization is lower than the cost of other classical structures [3].

The Figure 3 presents a conventional armature of a permanent magnet brush DC motor used in an automotive application. One can notice that the yoke with a relatively high number of slots is made of laminations. The important copper volume of the end-windings is typical of a lap winding used in a motor with a small axial length and an important airgap diameter.

Fig. 7. Armature of a conventional Brush DC motor for an automotive application (lap winding and yoke made of laminated material)

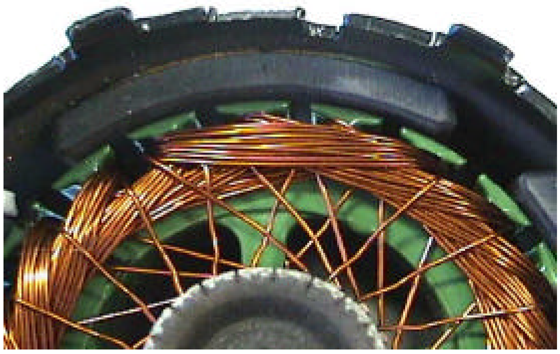
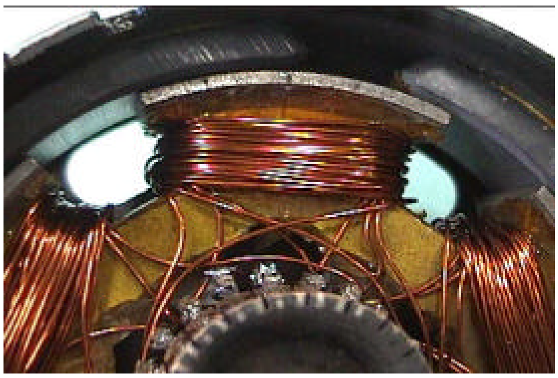


Fig. 8. SMC Armature of a Brush DC motor for an automotive application (concentrated winding and axially inserted end-windings)



The Figure 8 presents the armature of a permanent magnet brush DC motor with a concentrated winding structure, which was designed to meet the specifications of the motor of Figure 7, in terms of torque, speed, temperature rise and overall dimensions. One can notice that the armature yoke is made of Soft Magnetic Composites and that the end-windings are axially inserted. A suitable combination of the numbers of slots and poles have been selected to design a concentrated winding structure with high torque to current ratio [2].

The use of such a winding structure allows a gain of 70% on the volume of copper used in the lap winding structure [11].

The universal or AC commutator motor, widely used in hand tools or domestic appliances is generally using a 2 poles stator with a concentrated winding and an armature with interlocked coils elements. The copper volume and the axial length of the end windings of such conventional structures are then usually very important. A new universal motor structure based on an efficient use of the isotropic magnetic properties of the Soft Magnetic Composites and on the concentrated winding technique has been realized. The stator core presents a claw pole structure and the armature has a concentrated winding with several coils wound around the same tooth. With this new AC commutator motor structure, a reduction of the total volume by a ratio equal to 200% is obtained when compared to a classical universal motor structure with nearly identical performance.

Fig. 9. SMC prototype and conventional universal motor

Because the Soft Magnetic Composites materials present isotropic magnetic properties and low eddy current losses, it is now possible to use claw structures with acceptable magnetic losses in AC current supply applications.

A SMC prototype of claw-pole universal motor with 6 claws on the stator, 7 armature slots and 42 commutator segments has been realized, with the specifications of an existing motor made with laminations [10]. Fig.9 presents these motors. In the SMC prototype, the magnetic structure of the stator is divided in two identical parts which can be easily realized by a conventional powder metallurgy pressing process. The stator winding, made of only one simple coil element, is inserted in the magnetic parts of the claw structure of the stator to produce 6 magnetic poles in the air gap. A specific concentrated winding with several coil elements mounted on the same tooth is used for the armature. Because this kind of winding arrangement is reducing the number of turns per coil, the commutation inductance is minimized and the current commutation is improved [10]. The association of a claw-pole stator structure to an armature with a low number of slots and a concentrated winding is very efficient in terms of minimization of the motor axial length and production cost.

D. Brushless permanent-magnet motors

A similar design approach can be applied to the stator of Permanent Magnet Brushless DC motors. In this case, the use of windings concentrated around the teeth is presenting the same advantages: the volume of copper used in the end-windings is reduced in significant proportions. This gain is increasing if the axial length of the machine is small. The Joule losses are decreased and the efficiency of the motor is improved when compared to conventional structures.

In the case of the three-phase machines, the concentrated winding is too often associated and restricted to a winding with a short pitch of 120 electric degrees, i.e. to a winding with performances reduced compared to the traditional structures. But there is a significant number structures of polyphase machines which can support a concentrated winding, if the number of poles is increased. The authors have already shown that an efficient use of the concentrated winding technique can be used in two kinds of structures [13]:

- the structures with a regular distribution of slots (slots with equal widths), which present a fractional number of slots per pole and per phase,
- the structures with an irregular distribution of slots (slots with different widths) which are simplified versions of conventional machines.

A systematic method has been proposed for the determination of the windings [1] [5] [13].

The magnetic circuit of all these structures is well adapted to the use of Soft Magnetic Composites. They are using a lower number of slots than in the case of conventional machines, and the slot size is larger. With such stator shapes, the production process of the SMC parts is easier and cheaper. The isotropic properties of SMC can also be used to improve the performance by an axial insertion of the endwindings [11] and to maximize the copper filling factor by rounding the tooth plots.

Figure 10 to 12 present two Brushless DC PM motors which have been designed to meet the specifications of an electric fan widely used in the automotive industry [1]. This commercial fan is using a conventional PM DC motor with a lap winding, which is presented in the left part of Figure 12. Two brushless PM motors with an outer rotor structure (cf Fig. 10, 11) and a stator made of the iron/resin composite material ATOMET EM-1 have been realized. They are using a concentrated winding structure. One motor is using a regular distribution of slots (cf Fig. 10) and the other one is using an irregular distribution of slots (cf Fig. 11).

Fig. 10. Brushless DC motor for an automotive electric fan (stator with concentrated winding, yoke made of SMC)

Fig. 11. SMC stator of a Brushless DC motor for an automotive electric fan (concentrated winding, irregular distribution of slots)

One can notice on Fig.12 that the copper volume of the endwindings is much lower in the brushless motor with the concentrated winding than in the original PM DC motor with a lap winding. This volume of copper is 67% lower than in the original DC motor [1]. This gain could be improved by an axial insertion of the endwindings which was not used in this case.

Fig. 12. Comparative analysis of the Copper volume of the endwindings in the armature of a conventional Brush DC motor with a lap winding and the SMC stator of a Brushless DC motor with concentrated winding (same application and specifications)

V. CONCLUSION

The Soft Magnetic Composites is a new technology of magnetic material which presents interesting features for the production of electromagnetic devices. This paper demonstrates that an efficient use of a new technology of magnetic material needs a new structural design approach taking account of the advantages and constraints of the material. Several specific structures of SMC devices have been presented for a wide range of applications. These structures are well adapted to the use of SMC material and to a direct pressing process in a single operation. The total production cost is then minimized.

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