Use of soft magnetic composite materials in industrial applications.

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ABSTRACT

Insulated iron powders are alternative materials to conventional soft magnetic materials such as steel sheet laminations used in electrical machines. Most of the magnetic structures of existing electrical machines with AC excitation were optimized during the 20th century for 2D flux circulation in laminated yokes. Now with the isotropic composite materials new designs can be used to optimize the materials in terms of technical and economic performance. The 3D design optimization permits to meet the application specifications taking into account the magnetic, thermal and mechanical properties of the materials as well as the cost of the production and assembly process. In this paper, the characteristics and properties of typical composite powders are presented together with a design optimization methodology. This methodology was successfully adopted for investigating the potential applications of composite powders in several sectors such as automotive, electro-domestic and lighting industry.

INTRODUCTION

The soft magnetic materials traditionally used in AC applications are steel laminations. Now there are also iron-based powders specifically engineered for magnetic applications in alternating fields called soft magnetic composites or SMC. Although they have lower maximum permeability and magnetic induction than laminations, they possess isotropic properties that give end users and designers the possibility to make various electromagnetic devices with a topology more adapted to the final application. Also an important feature of SMC that contributes to their increasing acceptance is the ease of prototyping. Therefore the preferred approach for the feasibility study of a given project, consists in modeling of the application, design optimization and building of a prototype by machining a larger workpiece of pressed SMC.

Some characteristics and properties of two SMC materials are presented together with a design optimization methodology. This latter was successfully adopted for investigating the potential applications of SMC and examples are presented in the automotive (brush & brushless DC motors), electrodomestic (universal motor) and lighting industries (inductor).

SMC CHARACTERISTICS AND PROPERTIES

SMC are iron particles insulated from each other by a thin organic or inorganic film. The thin film acts primarily as an electrical barrier to reduce or suppress Eddy currents in AC applications and also as a mechanical strengthener after consolidation by pressing and heat treating at low to moderate temperatures. Two types of SMC materials are manufactured by QMP that cover the low to medium frequency range of applications. Some of their characteristics are given in Table I.

Table I. Characteristics of the ATOMET EM-1 and EM-2 materials used for low to medium frrequency applications.

Material	ATOMET EM-1	ATOMET EM-2
Description	Iron-resin	Iron-dielectric
Apparent density	2.80 g/cm³	3.00 g/cm³
Hall flow rate	28 s/50 g	28 s/50 g
Compaction	External lubrication	Conventional
Curing (30 min)	200 - 325°C	350 - 500°C
Resistivity	200 - 500 µohm-m	10 - 100 µohm-m
Applications	50 - 20000 Hz	50 - 400 Hz

ATOMET EM-1 is an iron-resin material system which requires lubrication of the die walls during compaction [1]. After pressing, parts are cured at low temperature in air (200°C to 325°C) to cross-link the resin and achieve high strength. ATOMET EM-2 is an iron-dielectric material in which the dielectric acts as a lubricant during the compaction as well as an insulator after a moderate temperature heat treatment, typically between 350°C and 500°C [2]. While EM-1 can be used in a very large range of frequency applications, EM-2 is rather intended for applications below 400 Hz and is particularly suitable for pressing complex shapes.

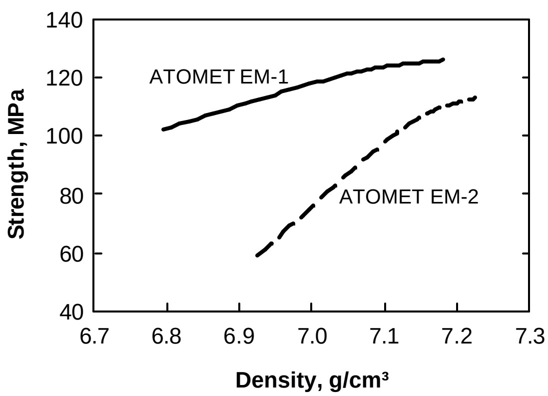

Figure 1. Effect of density on the mechanical strength of TR bars pressed from two SMC

The mechanical and magnetic properties of such dielectromagnetics are dependent on the density and heat treatment temperature, similar to any other powdered metal part. For example, the mechanical strength of ATOMET EM-1 cured at 200°C and ATOMET EM-2 treated at 350°C is illustrated in Figure 1 as a function of the density. The ATOMET EM-1 iron-resin material exhibits the highest values, up to 125 MPa at a density of about 7.20 g/cm³. The strength of the ATOMET EM-2 iron-dielectric material is more density-dependent and values as high as 110 MPa at densities above 7.20 g/cm³ can be reached.

The effect of density on the magnetic induction is presented in Figure 2. Induction is proportional to the density and not greatly affected by the mix formulation. It can be described by the linear relationship given in fig. 2. The effect of density on the AC losses at 1 Tesla (60 Hz & 400 Hz) is presented in Figure 3. The AC losses decrease with an increase in density which can be attributed to

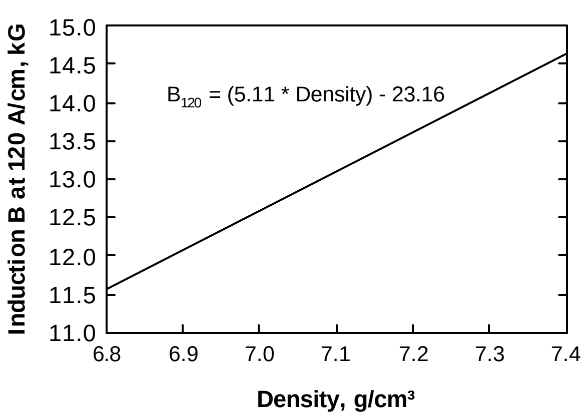

Figure 2. Effect of density of SMC materials on the magnetic induction at an applied field of 120 A/cm.

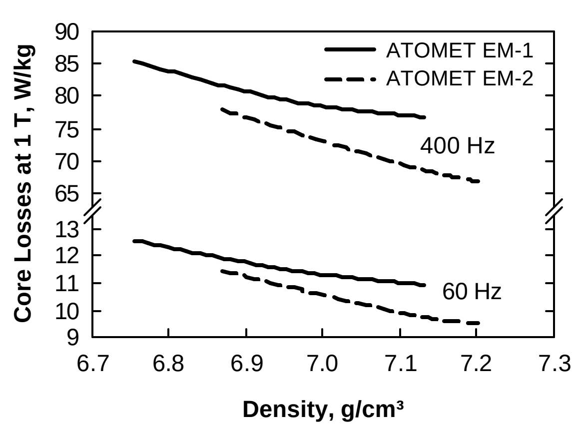

Figure 3. Effect of density on the total core losses at 1 Tesla measured at 60 and 400 Hz.

a decrease in the hysteresis loss. Indeed, with powdered materials, as the density increases magnetization becomes easier (higher permeability and lower coercive force) that translates into a decrease of the hysteresis portion of the core loss. The iron-dielectric ATOMET EM-2 material shows losses approximately 12% lower than for ATOMET EM-1. This is due to the 350°C heat treatment that slightly reduces the hysteresis loss in this material. At densities above 7.0 g/cm³, losses at 1 T are about 10 W/kg at 60 Hz and 70 W/kg at 400 Hz. The fact that the AC losses are proportional to the frequency and not to the square of the frequency, is a good indication that the insulation is efficient and eddy currents remain low, even in ATOMET EM-2, which has a lower resistivity.

SMC AND DESIGN OF ELECTROMAGNETIC DEVICES

For any application, electrical machine designers must find an optimal compromise between the specifications, topological structures, device dimensions, material properties and production process costs. The characteristics of the soft magnetic material technology that is used have a strong influence on the optimal design solution. Now in addition to the various traditional steel sheet laminations, SMC are also available. Hence for each soft magnetic material option, there is a specific optimal solution because the magnetic, thermal and mechanical properties, as well as the cost of production and assembly process may be different.

The steel sheet lamination technology takes advantage of high saturation induction and high permeability of iron with limited Eddy current losses. Several grades of laminated materials have been developed in order to adapt to different specifications and cost-performance compromises for a wide range of applications. But this well established and efficient technology also presents some drawbacks: several production steps required to realize a typical magnetic circuit, low heat dissipation coefficient in the direction perpendicular to the plane of the laminations, significant scrap loss during the punching process, difficult and expensive recycling process for electrical machine armatures and as the frequency of the application increases, the use of laminated materials is limited by the cost, feasibility and processing of thin sheets.

In the past, designers have developed and optimized electromagnetic structures only for 2D magnetic flux circulation. This specific constraint of the laminated material technology has limited the available number of topological structures that can be used to design electrical machines. Despite their relatively low values of unsaturated permeability, the SMC present many interesting characteristics, which can improve the performance of electromagnetic devices, if they are properly used during the design process: - the number of production steps can be reduced (magnetic circuit pressed in a single operation or assembled from several pre-pressed parts) - high performance magnetic structures can be designed with complex shapes, which are too difficult or too expensive to realize with laminated materials [3,4,5] - the magnetic isotropy allows the design of new electrical machine structures with a 3D circulation of the magnetic flux that can reduce the weight of the inactive copper, simplify the machine windings and reduce their production cost [6,7] - the thermal isotropy and good thermal conductivity improve the heat dissipation (from the whole external surface) of electromagnetic devices [4,6,8] - the vibrations and audible noise of electromagnetic devices can be reduced [8] - the recycling process of electrical machine armatures is improved because the separation of iron powder and copper is easier than in the case of laminations [9] – and finally an integrated design approach can be applied where the thermal, electromagnetic and mechanical functions can be integrated in a single part [6].

A specific methodology to design electrical machines with SMC for a wide range of applications was developed. The flowchart of this design environment is illustrated in Figure 4. There are three main steps in the design process:

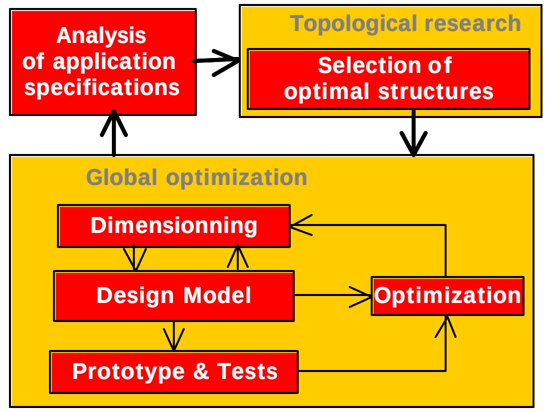

Figure 4. Design optimization methodology

During the first step, a detailed analysis of the application specifications is performed. Electromagnetic devices can be used as electromagnetic energy storage (filtering inductors), as electrical energy converters (transformers) or electromechanical converters (motors or generators). There are input and output specifications which can be dimensional, thermal, electrical (power, voltage, current, frequency, power factor, etc.) or mechanical (rated torque, transient torque, rated speed, speed range or torque-speed characteristics, etc.). All these specifications are formulated as constraint functions of the design variables. Because there are usually many design solutions, it is necessary to determine some kind of objective function to maximize or minimize, such as energy, power/torque-to-weight ratio, efficiency, or some other cost-performance ratio taking into account the production constraints.

The second design step is the topological research. Several competitive structures of electromagnetic devices are selected among the multiple electrical machine structures which can respect the specifications and maximize or minimize the objective function. Conventional 2D or 3D structures and original solutions can be chosen among the multiple topological solutions offered by the use of the SMC.

The third design step is the global optimization process. This efficient CAD tool is used to determine the optimal values of the design variables of each topological structure selected during the previous step (dimensions, current and magnetic flux densities, etc.). It includes several modeling tools that are coupled together, each tool modeling one specific aspect: thermal, electrical, mechanical, magnetic, material and even production constraints. The loop in this third design step is usually closed by the building of a real prototype and testing.

This global optimization methodology has been successfully adopted in a wide range of SMC applications. Some of them are described in the following section.

EXAMPLES OF SMC APPLICATIONS

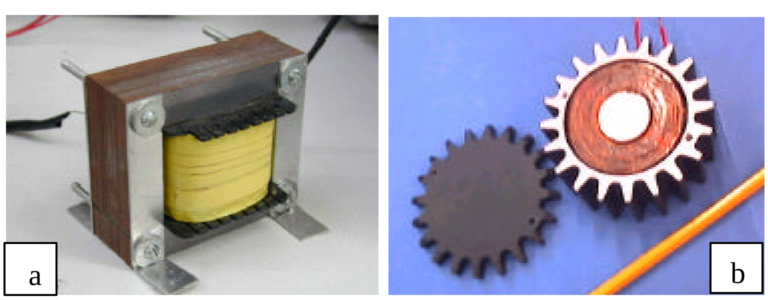

Figure 5. Inductor used in a lamp ballast: a) Laminated structure; b) SMC pot core structure with magnetically active cooling fins.

A) Inductor for a lighting application.

In this example, the laminated inductor core of a passive power factor correction system used in a 250 W fluorescent lamp ballast was investigated (220 V–60 Hz). Owing to the isotropy of the magnetic and thermal properties of SMC, a pot core geometry with integrated cooling fins was retained that provided very interesting characteristics. The two inductor structures are shown in Figure 5. The pot core structure is easy to press in two parts, the winding can be made separately and inserted during the assembly process, EMI is minimal since windings are totally enclosed and shielded and the hum is reduced (no vibrations compared to lamination stacks). Also, the integrated cooling fins on the external surface, which also carry the magnetic flux (magnetically active), greatly improve the thermal dissipation and efficiency. For instance, with the SMC inductor, total losses were reduced by 30%, occupied volume by 25%, weight by 10% and temperature rise by 25% [10].

B) Permanent magnet brush & brushless DC motors for an automotive application.

The laminated and SMC armatures (inner rotor) of a 180 W brush DC motor for an automotive electrical fan are shown in Figure 6. The conventional armature magnetic circuit is made with a laminated material and distributed windings with bulky end windings. The inactive copper of the end windings lowers the motor efficiency and increases the total axial length of the motor as well as its production cost. The SMC structural solution uses multi-layer concentrated windings with a small number of large slots. The total axial length of the motor and the copper volume are thus reduced without decreasing the motor performance. In fact, this structure is well suited to the production process of P/M parts, improves the motor performance and minimizes the production cost. The comparative analysis of the two structures demonstrated that a 50% reduction in copper volume is achieved for the same specifications of the motor in terms of torque, speed, temperature rise and overall dimensions [11].

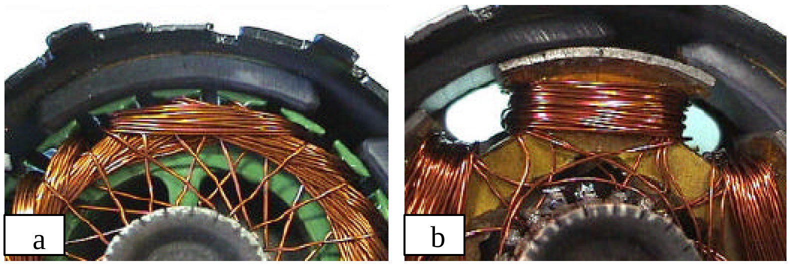

Figure 6. Armature of a brush DC motor: a) laminated structure with lap winding; b) SMC structure with concentrated windings.

A similar SMC structural solution using multi-layer concentrated windings with a small number of large slots was applied to the stator of a permanent magnet brushless DC motor to meet the specifications of an electric fan employing a conventional brush DC motor with a lap winding. The two motors are shown in Figure 7. In this case, the weight and diameter of the motor were reduced and the use of concentrated windings reduced the quantity of copper by 67% [3].

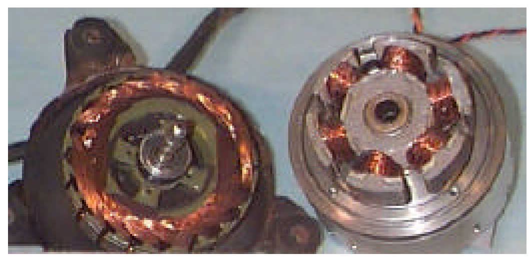
Figure 7. Conventional brush DC motor with a lap winding and the SMC stator of a brushless DC motor with a concentrated winding.

C) Universal motor for an electrodomestic application.

Many chorded hand tools or domestic appliances use a universal motor or AC commutator motor. The typical version has a 2 pole stator with a concentrated field winding and an armature with conventional distributed windings. The copper volume and the axial length of the stator and rotor end windings of such conventional structures are thus usually very large. A new SMC universal motor with a claw structure for the stator and a concentrated winding armature has been developed for the same application. The laminated and SMC structures are illustrated in Figure 8.


Figure 8. Conventional laminated universal motor (left) and SMC motor (right).

Such a stator claw structure arrangement makes the assembly process very simple and can minimize the total stator weight if the number of poles is increased. However, in this kind of AC motor, the stator magnetic flux is alternative and the iron losses can be important in the yoke and claws. Isotropic SMC materials like ATOMET EM-1 with relatively low magnetic losses are then very well adapted to such an application. The motor armature has a concentrated winding structure where the coils are wound around the rotor teeth [7]. This technique facilitates fabrication and reduces the number of slots, copper volume and total axial length of the motor without decreasing its performance [5,7]. This new universal motor structure has been designed according to the previous methodology in order to meet the specifications of an existing laminated universal motor. A reduction of the total motor volume by a ratio equal to 200% has been obtained.

CONCLUSION

Soft magnetic composites bring new degrees of freedom to design structures of electro-magnetic devices and new topological structures can now be utilized. Because it is a new technology, the expert data derived from one century of industrial experience based on laminated materials cannot be used. A systematic design optimization methodology has been developed to achieve optimal use of the SMC in terms of technical and economic performance. This design approach has been successfully adopted by the authors in a wide range of industrial applications. The results show that the SMC technology can be an interesting alternative to the laminated technology when designers try to make an optimal compromise between their advantages and their drawbacks in terms of machine structure.

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