Application of Soft Magnetic Composite Materials in Electrical Machines: A Review

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SUMMARY: *Soft magnetic composite (SMC) materials and their application in electrical machines have undergone significant development in the past decade. The major advantages of the materials include isotropic magnetic and thermal properties, very low eddy current loss and relatively low total core loss at medium and higher frequencies, and nearly net-shape low cost fabrication process with good tolerance and surface finish by using the well developed powder metallurgical techniques (no need of further machining). It is even anticipated that the application of SMC may lead to a revolutionary development in the electrical machine manufacturing industry. This paper reviews the study about the application of SMC in electrical machines by the authors and other researchers. Both successful experiences and existing difficulties are discussed, and possible further work required for the commercial success of SMC machines is proposed.*

1 INTRODUCTION

Soft magnetic composite (SMC) materials, produced by powder metallurgy techniques, possess a number of advantages over traditional laminated silicon steels commonly used in electromagnetic devices and have undergone a significant development in the past decade.[1,2] The basis for the material is the bonded iron powder of high purity and compressibility. The powder particles are bonded with a coating of an organic material, which produces high electrical resistivity. The coated powder is then pressed into a solid material using a die and finally heat treated to anneal and cure the bond.[3]

This type of material is, in general, magnetically isotropic due to its powdered nature, creating key design benefits.[4] The magnetic circuits can be designed with a three-dimensional (3D) field path. Different radical topologies can be exploited to achieve high motor performances, for the reason that the magnetic field does not have to flow within a two-dimensional (2D) plane such as that in laminated steels. New fabrication methods and previously impossible features (i.e. the core back, teeth and airgap may take different axial lengths) can now be obtained. Therefore, by using SMC, developers may regain the control over motor size, shape and potential output, such that motors can be designed to suit the applications, not the reverse.[1]

The isotropic thermal property of SMC materials is also advantageous in increasing heat dissipation. For laminated steels, the thermal conductivity in the direction perpendicular to the lamination plane is much lower than that within the plane. This implies that in laminated cores the heat is transferred almost uniquely at lamination edges.

Because the iron particles are insulated by the surface coating and adhesive, which is used for composite bonding, the eddy current loss is much lower than that in laminated steels, especially at higher frequencies. The total loss is dominated by hysteresis loss, which is higher than that of laminated steels due to the particle deformation during compaction. For example, at the power frequency of 50 Hz and the peak flux density of 1.5 T, the total core loss in SOMALOY™ 500 (with 0.5% Kenolube), a new soft magnetic composite developed by Höganäs AB, Sweden, is 14 W/kg, double that of even the low grade Kawasaki 65RM800 (0.65 mm thick, 28 x 10^{-8} Ωm).[5,6] When the excitation frequency increases, however, the increment of core loss in SMC is smaller than that in electrical steels due to the much smaller eddy currents. At 400 Hz and 1.5 T peak the total core loss in SOMALOY™ 500 is 120 W/kg, the same as the low-medium grade Kawasaki 50RM700 (0.5 mm thick, 28 x 10^{-8} Ωm). High grade Kawasaki 35RM270 (0.35 mm thick, 54 x 10^{-8} Ωm) has one third the loss then, i.e. 40 W/kg at 400 Hz and 1.5 T peak.

Another comparison is with the commonly known data for C cores of transformers which are about 2 W/kg at 50 Hz and 1.5 T peak, and 13 W/kg at 400 Hz and 1 T peak.[7] It is noted that SMC materials have higher total core loss than common laminated steels, especially in the low frequency range. Therefore, SMC materials are more likely to be better used for motors operating at higher excitation frequencies, but they are not yet as good as high grade laminations at low and medium frequencies and any superior performance must come from exploring 3D flux motor topologies or some other SMC features.

The use of SMC creates the prospect of large volume manufacturing of low cost motors. Because the iron cores and parts can be pressed in a die into the desired shape and dimensions, further machining is minimised and hence the production cost can be greatly reduced.

Unlike laminated steels, SMC parts can be made with smooth corners in the teeth. This allows thinner slot insulation, resulting in better heat dissipation and more room for the winding.[4]

The most important advantage of SMC materials may be the cost effective and environmentally friendly manufacturing, with minimum material waste, by using the well-developed powder metallurgical techniques. These techniques can be up to 50% more cost-effective than conventional production. Because of the significant economical, social and environmental benefits, the study about the application of SMC materials in electrical machines may lead to a revolutionary development in the electrical machine manufacturing industry.[1]

To investigate the application potential of SMC materials in electrical machines, some researchers, such as those in the University of Newcastle upon Tyne, UK, Aachen University, Germany, Laval University, Canada, and our research group in the Centre for Electrical Machines and Power Electronics (CEMPE), University of Technology, Sydney (UTS), Australia, have been working in this field for several years and the results appear to be promising.[8-23]

In spite of the favourable magnetic and thermal properties mentioned above, SMC materials have some noticeable disadvantages that should be carefully considered in the design, manufacture and application of electrical machines. The permeability of SMC material is dramatically lower than that of electrical steels because it contains non-ferromagnetic materials. Best values of maximum relative permeability are 500 for SOMALOY™ 500 or 550 for SOMALOY™ 550.[5,24] Therefore, it is anticipated that this material will be appropriate for construction of permanent magnet (PM) motors for which the magnetic reluctance of the magnet dominates the magnetic circuit, making such motors less sensitive to the permeability of the core than armature magnetised machines, such as induction and reluctance machines.[4]

SMC materials have higher hysteresis loss resulting from strain and poor domain structure, lower saturation flux density than that of the base iron powder (2.18 T for perfectly aligned iron) due to the distributed air gaps and non-ferromagnetic coating/binder in the material, and lower mechanical strength especially when high powder density is sought.

Because of the significant differences in magnetic, thermal and mechanical properties, simply replacing the existing laminated iron core in an electrical machine with an SMC material will result in a loss of performance with very small compensating benefits. To take full advantages of the SMC material and overcome its disadvantages, a great amount of research work is required to gain better understanding of the material properties, novel motor topologies, advanced field analysis, design and optimisation techniques, and appropriate power electronic drive system.

This paper aims to review the study on SMC machines by the authors and other researchers. Different topologies of motors have been investigated. It is found that SMC materials are to be most easily applied in machines that need a higher frequency, benefit from a 3D magnetic flux path, and have a big effective airgap (i.e. PM motors) in comparison to iron circuits. Although encouraging progress has been achieved, a large amount of work is still required for commercial success.

2 DEVELOPMENT OF SMC MATERIALS – FOR USE IN ELECTRICAL MACHINES

2.1 Background

Although the initial idea to apply soft magnetic composites made from iron powders in electrical machines was proposed as early as the 19th century, it had not attracted serious attention until the 1980s.[25] In 1990, Kordecki and Weglinski described several soft magnetic powder composites and the problems associated with their applications as magnetic cores in electrical converters.[25] In 1992, Jansson reported the product process and properties of SMC materials for AC applications.[26] Since then, investigation on development of SMC materials and their application in electrical machines has intensified and encouraging progress has been achieved.

Besides the advances of raw materials and technologies, market need is the primary drive for the development of these materials. Nowadays, electrical micromotors and low power motors are widely used in automation, robotics, and office and home apparatus. Their production has reached millions of pieces per year.[25] In general, the core structure and the magnetic flux path are very complex and construction by lamination steels is very difficult, and sometimes impossible. Solid steels suffer excessive eddy current losses. Secondly, the powder composites can be produced at a very high rate, providing an obvious economic advantage. Furthermore, the SMC materials reveal design freedom, a key benefit, for motor designers because the powdered nature means magnetic and thermal isotropy and many constraints imposed by electrical steels are avoided.

In 1995, Persson *et al.* reported the compaction process and advantages of powder metallurgy techniques, design and magnetic properties of surface coated iron powders, and the SMC materials' application in an axial field PM motor.[8] The important properties of the materials for electrical machine application, such as iron loss, unsaturated permeability, magnetic and thermal isotropy, and production techniques were discussed.

2.2 Powder Metallurgy

SMC materials are produced by the powder metallurgy technique, a well-known cost-effective method for mass production of net shape or near net shape magnetic parts (no need of further machining). The major advantages of this technique include high material utilisation, precise material control, and the ability to produce relatively complex shapes.[8] Figure 1 illustrates the powder metallurgy compaction process. One of the important stages in the compaction process is to prepare the premix feed, which includes base powder, lubricant and other additives, and determines the material characteristics.

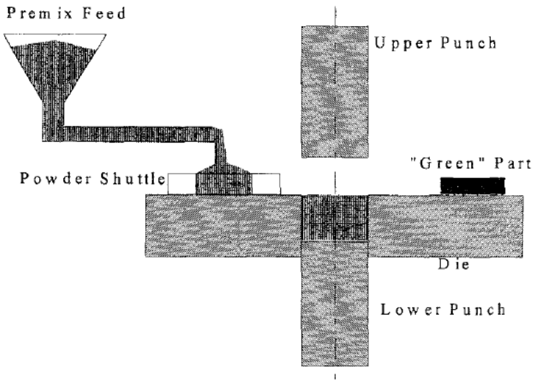

Figure 1: Powder metallurgy compaction process [8]

By the technique outlined in Figure 1, a number of soft magnetic materials have been produced. Special alloys, such as phosphorous-alloyed steels, can only be produced by powder metallurgy. The use of these materials for constructing magnetic circuits in varying magnetic field applications, however, is limited by the relatively high eddy current losses occurring in the solid material.[8]

SMC materials for electrical machine applications use the premix and compacting techniques of powder metallurgy. Each iron powder particle of SMC has a thin organic surface insulation. The insulation layer remains intact after compacting at high pressure and thus SMC offers low eddy current loss in all directions. Electrical machines can now be designed for higher frequency applications.[27]

2.3 Design of Materials

SMC materials are designed for use in electrical machines, particularly those with frequencies ranging from 50 to several hundred, or thousand hertz. The magnetisation should be at a high level. Therefore a high purity, highly compressible iron powder with an electrically insulating layer has been used as the base material. The use of pure iron is motivated by the fact that the presence of alloying elements reduces the saturation induction while iron has the highest saturation induction with the exception of cobalt/iron. The insulation layer on the surface of the iron particle reduces the eddy current in all directions. In order to ensure high induction at low field strength, high mass density is required. High compressibility iron powder with a minimum thickness of insulation layer is combined with high compacting pressure in order to achieve high induction.[27]

Figure 2 illustrates the schematic design of SMC materials. A lubricant, Kenolube, is added to the base powder for reducing friction and wear on compacting tools. The addition of lubricant should be in the lowest possible quantity since it will reduce the mass density of the compact. To increase the mechanical strength a phenolic resin binder can be added. The content of binder should also be kept to a minimum for high mass density.[8]

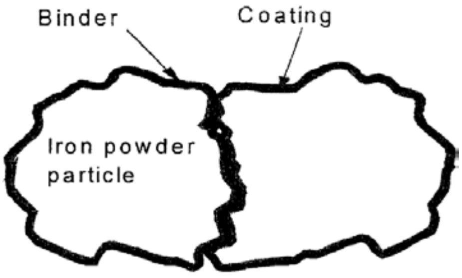

Figure 2: Schematic design of material [8]

2.4 Product Technique

By the use of the powder metallurgy technique, SMC parts require no subsequent treatment other than curing at a temperature of about 500 °C. In terms of production efficiency and material utilisation, SMCs and the powder metallurgical process offer major advantages over the traditional lamination technology, which is widely used in the manufacturing of transformers and rotating electrical machines. The mass production cost using this technology could be very low.

Production technique is the area where the largest changes need to be made, and where the greatest benefit is possible. The desired method of production is a die pressing operation followed by heat treatment. The production of a conventional geometry core in this way is likely to be competitive in many applications, with windings added afterwards using existing techniques. For larger machines, it is advisable to use as few components and as identical components as possible in order to increase assembly simplicity and reduce the production cost.

2.5 SMC Characteristics for Electrical Machine Application

SMC materials possess both advantages and disadvantages as described in the Introduction section. It should be emphasized that multiple benefits can accrue from the synthesis of powder metallurgy and machine design, as summarised in the following:

(1) The magnetic performance can be tailored to meet the needs of individual applications by modifying particle size distribution, additives and thermal treatment;

(2) SMC materials are both thermally and magnetically isotropic and offer new design opportunities such as linear performance (no saturation) at high fields;

(3) The component's stable dimensions after processing (compaction, curing and heat treatment) means that very tight tolerances are achievable, and net shape designs can fully exploit the SMC materials' 3D flux capability;

(4) The production process is simple. After a normal powder metallurgical compaction, only a simple curing is needed to finish the SMC net part shape, and a subsequent heat treatment at up to 500 °C in air improves medium frequency performance, reducing losses even further; and

(5) SMC materials are designed for a wide variety of applications, ranging from traditional iron powder core to new and revolutionary possibilities, e.g. linear property transformers and ignition systems, and electrical machines with high torque-to-volume ratio.

2.6 Commercial SMC Products

A series of SMC products have been developed by Höganäs AB, Sweden, a world leading manufacturer, including Permite™ 75, ABM100.32, SOMALOY™ 500 and SOMALOY™ 550.

The iron powder ABM100.32 is surface insulated and can be combined with a lubricant or both lubricant and resin to achieve a variety of premixes.[27] The magnetic properties are dictated by a combination of the final mass density and the heat treat temperature; the former is dictated by the compacting process.

Although necessary, the addition of organic materials is detrimental to the compressibility of the powder. The material ABM100.32 with 0.5% Kenolube as lubricant achieves densities ranging from 7.2 kg/cm^3 to 7.3 kg/cm^3. However, the tensile strength is limited to a range of 25 MPa to 45 MPa. In order to increase the strength a resin addition is required. The material ABM 100.32 with 0.5% Kenolube as lubricate and 0.5% phenolic resin has a density range from 7.0 kg/cm^3 to 7.1 kg/cm^3. The tensile strength range is then from 50 MPa to 60 Mpa.[8]

The ideal solution is the addition of a lubricating resin so the total amount of organic material can be reduced. The introduction of the warm compacting technique further enhances the density. Trials with this technique and a high temperature lubricating resin have achieved a density of 7.35 g/cm^3 combined with strength of 90 Mpa.[8]

Compared to Lycore-130, which has a tensile strength of 500 Mpa,[28] SMC has a much lower strength (50-90 Mpa). However, the mechanical strength of a device is basically determined by the strength of the weakest component, e.g. the permanent magnets. The mechanical strength of SMC is similar to that of PMs because the same fabrication approach is used. Therefore, the mechanical strength of SMC is not a serious problem, though special attention is still required according to the authors' experience.

SOMALOY™ 500 was specifically developed for soft magnetic applications, such as electrical machines, transformers, ignition systems and sensors, with 3D magnetic fields. SOMALOY™ 500 is available in a variety of press-ready mixes (called 'premixes'), each of which optimises a specific property of the final component. Optimum magnetic properties are achieved with the premix containing lubricant only, which is recommended for conventional powder-metallurgical compacting. The unique features of SOMALOY™ 500 include a saturation magnetic flux density of 2.03 T, a maximum relative permeability of 500, and a low total loss at medium frequency. The premix containing 0.6% lubricating binder (LB1) is recommended for both conventional and warm compacting. The addition of LB1 lends to higher strength to the composite. Magnetic properties such as hysteresis curve, typical B-H curve, core loss and permeability can be found from Höganäs catalogs.[5]

Other SMC materials available are PERMEDYN™ LF1, MF1, MF2 and MF4 by ETREMA Products Inc.,[29] PREMAG TP2803 by PREMIX OY, Finland,[30] and ATOMET EM-1 by Quebec Metal Powders Ltd. Canada.[31] However, for various reasons, most applications so far have used SOMALOY™ 500 by Höganäs AB, Sweden, although the Laval University group, Canada, used ATOMET EM-1 for their research.[17-19]

3 DEVELOPMENT OF SMC MOTORS

To develop the practical design and construction techniques for SMC motors and to confirm the theory, different types of motor prototypes have been designed, manufactured and tested by the authors and other researchers.

Early attempts of using SMC in motor construction started in 1980s,[32-35] but due to various reasons the motor performance was far from satisfactory.

Since 1995, the research group of the Newcastle University, UK, in collaboration with Höganäs AB, Sweden, studied various types of SMC motors including axial field motor,[8] transverse flux,[9] claw pole,[10,11,12] PM servo,[13] hybrid axial and radial flux,[14] and universal motors[15] for different applications.

The first SMC motor investigated by the group was an axial field machine, the most straightforward form suggested by the SMC preforms provided. The motor was a double-sided PM motor with a toroidally wound stator. Production of the slotted stators of axial field machines normally requires spirally wound laminations, making slotting very difficult. SMC materials offer an obvious manufacturing advantage. The SMC material used for the stator was ABM100.32.

The use of SMC in transverse flux geometry was first attempted in 1996.[9] The 3-phase 3-stack transverse flux motor (TFM) was designed with a novel structure using SMC core. It can achieve very high specific torque due to high operating frequency (the machines have 100 poles). Considering that each stack forms a phase and is magnetically independent from the others, a single-phase prototype was constructed. The major dimensions of the TFM prototype include: stator outside diameter of 362 mm, overall axial length of 60 mm, rotor outside diameter of 300 mm, rotor inside diameter, and main (axial) airgap length of 0.5 mm. Some results have been obtained from the test on the prototype, such as a specific torque of 12.35 Nm/kg of active mass. However, the actual operational performance as a motor, which is normally of multi-phases, cannot be obtained directly.

In 1997, the Newcastle group reported a PM machine with an SMC claw pole armature.[10] Optimum design of the machine was not attempted. The prototype machine has a stator outside diameter of 200 mm, stator inside diameter of 117 mm, axial length of 37.5 mm, and main airgap length of 0.5 mm. The number of poles is 24, so the rated operational speed is 1500 rpm when the frequency of the stator currents is 300 Hz. The prototype was claimed by the authors as a design validation tool only. It was tested successfully as a single-phase generator, delivering an average torque per unit active mass of about 3.3 Nm/kg, but the motor operation has not been reported.

In 1999, the UK Newcastle group presented a PM servo motor with SMC core and prepressed windings.[13] The design aimed to fully take advantage of SMCs' unique properties. The core back is axially extended over the end windings, utilising the magnetic isotropy of the powdered iron. The armature core is subdivided into tooth and core back sections, each of which could be easily pressed. The coils were prepressed and a very high fill factor (78%) was achieved.

Also in 1999, the group reported the design, construction and testing of a PM SMC motor with both axial and radial magnets.[14] The armature carries alternating flux in all three coordinate directions and thus SMC is an ideal candidate. The machine was designed as the drive motor for electric bicycles.

In 2000, the Newcastle group reported design and testing of an SMC universal motor for use in vacuum cleaners.[15] The isotropic magnetic properties of SMC offer freedom of core design to create better-shaped windings and saving in copper. The core is subdivided into poles and half-yokes, split on the axial centreline, allowing bobbin winding of the field and easy assembly.

Other research groups have followed the lead of the Newcastle group and investigated the use of SMC in motors. For example, Zhu and Howe in Sheffield University, UK, investigated the potential of using SMC in a high speed PM brushless DC motor.[36]

In 1997, Zhang and Profumo in Italy developed an axial flux PM brushless DC motor using SMC ABM100.32 supplied by Höganäs, and achieved a maximum efficiency of 68%.[37] The major dimensions include outer radius of 40 mm, inner radius of 25 mm, stator axial length of 20 mm, rotor axial length of 10 mm, and airgap length of 1 mm. The SMC prototype has 6 poles and is designed to operate at a rated speed of 2500 rpm; implying an operating frequency of 125 Hz. In 1998, they reported another axial flux motor with interior PM rotor made of powdered SMC.[38] However, the stator cores were realised by wound laminated iron and not much advantage of SMC has been explored.

In 2002, Cvetkovski *et al.* in Napier University, UK, presented the design of a PM disk motor by using SMC material.[39] The motor is a double-sided axial field motor with two stators and a centered PM rotor. Two types of stators were analysed: laminated and SMC stators.

Henneberger and his team at Aachen University, Germany, developed a transverse flux SMC motor in 2000.[16] Since the magnetic field in the transverse flux motor is 3D, it can benefit from the isotropic magnetic property of SMC materials.

Cros *et al.* in Laval University, Canada, used ATOMET EM-1, an iron/resin SMC material produced by Quebec Metal Powders Ltd. for their study. In 1998, they presented two prototypes of brushless PM motors with SMC core.[40] In 2001 they reported a brushed DC motor with concentrated windings and SMC armature.[18]

Also in 2001, Cros *et al.* reported their study of an SMC universal motor.[19] The stator used the claw pole structure and the magnetic circuits of both the stator and rotor were made of SMC materials (Atomet EM1). The use of SMC in universal motors can reduce the manufacturing cost, but the benefit becomes less significant as far as efficiency is concerned.

In April 2002, Phase Motion Control, an Italian servo motor manufacturer, started mass production of the “Ultract T” series of brushless servo motors based on SMC technology.[1] The mechanical performance of these SMC motors was mentioned as comparable with that of existing motors. Pole components are made individually by compacting and then wound and assembled in the motor. The coil fill factor can be very large and high torque density is achieved. In summary, the key technologies are new winding configuration, novel magnetic circuit, and SMC components.

Besides the rotating PM motors, other interesting applications of SMC include magnetic bearings,[41] actuators,[1] lighting applications such as inductors and electromagnetic ballasts,[42] and transformers.[43]

Our research team, the CEMPE at UTS, has established a significant level of expertise in SMC material and its effective application in electrical machines in the last few years. In 1998, the team started its research on development of low cost PM motors using new SMC materials, in collaboration with Höganäs. With the special strength in magnetic testing and modelling, the team firstly carried out a comprehensive study of the magnetic properties of SMC materials. The magnetic properties of SOMALOY^{TM} 500 have been measured under alternating and 2D rotating magnetic excitations.[44] Backed up by this advanced understanding and modelling of the magnetic properties of the material, the authors of this paper led the design and construction of a single-phase claw pole PM SMC motor,[45,46] a three-phase claw pole PM SMC motor,[20,21,22,47] and a three-phase transverse flux PM SMC motor.[20,23] The experimental results of the three SMC prototypes are very encouraging. The three-phase claw pole motor rated as 500 W at 1800 rpm achieved a maximum efficiency of 81%. The transverse flux prototype reached a maximum efficiency of 79.5% at the rated power (640W) and speed (1800 rpm), although the rotor yoke was, for simplicity of manufacture, made of mild steel. The eddy current loss in the mild steel reduced the overall efficiency by about 6%. The volume of the three-phase claw pole and the transverse flux motors is only half of that of an induction motor of the same power rating.

4 DISCUSSION AND FURTHER WORK

To investigate the potential of SMC materials the in manufacture of small motors of complex structures, various types of motors with SMC core have been designed and manufactured by different researchers. The performance of the prototypes is comparable to that of similar motors with electrical steel cores at potentially reduced manufacturing cost. The motor design method and performance analysis have been validated by experiments on the prototypes.

In spite of the encouraging progress, a large amount of work is still required for commercial success. The possible further work can be:

1) The magnetic properties of SMC under 3D magnetic field excitations need to be investigated for design of 3D flux motors.[48,49,50] Although quasi 3D magnetic properties have been measured by cutting the samples in different orientations,[44] the true 3D property can only be represented by the components of magnetic flux **B** and field strength **H** in all three axes.

2) To find an optimum SMC composition for the best compromise between the magnetic and mechanical properties, and to provide data and model for motor design.

3) In addition to the motor types that have been studied, more up to date high performance motor topologies and their suitability for SMC application need to be investigated. A qualitative comparison should be carried out to select several topologies that are likely to yield high performance with a low cost.

4) To develop and apply advanced design and performance analysis in developing SMC motors, such as the core loss analysis in the rotor yoke and the NdFeB magnets by FEA, thermal analysis by numerical method, and optimisation by use of modern techniques, such as genetic algorithm, neural network, fuzzy logic, etc.

5) To develop low cost inverters and sensorless SMC motor control algorithms. Generally, SMC machines are intended to use complex core structures (e.g. 3D flux topology) but a simple winding arrangement (e.g. global winding of a single concentrated coil). The simple electrical circuit can result in the use of a low-cost controller, which requires innovative, smart control algorithms to achieve high performance.

6) To develop SMC core manufacturing techniques using mould compaction/injection, in close collaboration with industry.

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