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Review

A Review of Electric Motors with Soft Magnetic Composite Cores for Electric Drives

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Abstract: Electric motors play a crucial role in modern industrial and domestic applications. With the trend of more and more electric drives, such as electric vehicles (EVs), the requirements for electric motors become higher and higher, e.g., high power density with good thermal dissipation and high reliability in harsh environments. Many efforts have been made to develop high performance electric motors, such as the application of advanced novel electromagnetic materials, modern control algorithms, advanced mathematical modeling, numerical computation, and artificial intelligence based optimization design techniques. Among many advanced magnetic materials, soft magnetic composite (SMC) appears very promising for developing novel electric motors, thanks to its many unique properties, such as magnetic and thermal isotropies, very low eddy current loss, and the prospect of low-cost mass production. This paper aims to present a comprehensive review about the application of SMC for developing various electric motors for electric drives, with emphasis on those with three-dimensional (3D) magnetic flux paths. The major techniques developed for designing the 3D flux SMC motors are also summarized, such as vectorial magnetic property characterization and system-level multi-discipline robust design optimization. Major challenges and possible future work in this area are also discussed.

Keywords: soft magnetic composite; electric motor; magnetic isotropy; three-dimensional magnetic flux

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1. Introduction

Transportation electrification has become a primary interest of research and application for handling urban pollution, in which advanced electric motor system plays a key role [1–4]. In electrified transport vehicles, the electric motor and associated drive system should be designed with high-efficiency, high-power-density, and high-reliability because the allowed volume and weight of the electric vehicles (EVs) are generally quite limited and they may operate in harsh environment like high temperature and vibration [5–10]. In past decades, many efforts have been made to develop high performance EV motors, such as advanced designs with multi-level multi-objective multi-physics and robust optimizations [11–16], modern control techniques with field oriented control, direct torque control, model predictive control schemes [17–23], and the application of various novel electromagnetic materials, such as high silicon electrical steels, amorphous ferromagnetic metals, high-temperature superconductors, and soft magnetic composite (SMC) materials [24–36].

Among various magnetic materials, SMC materials have attracted special attention for developing high-performance electric motors thanks to their many unique properties [33–42]. The basis of the material is a bonded iron powder of high purity and compressibility. The powder articles are bonded with an electronically insulating coating layer, resulting in very high electrical resistivity and ignorable eddy current loss. The coated powder is then pressed into components with desired shape and size using a mold, and finally heat treated to anneal and cure the bonding.

Due to its powder nature, the SMC material is magnetically and thermally isotropic in general. The magnetic isotropy and ignorable eddy current loss open up great design benefits as the constraints on the conventional electrical steel sheets are now removed. In the electrical machines with conventional laminated steels, the magnetic field must be designed to flow within the lamination plane, i.e., two-dimensional (2D), as any magnetic flux component perpendicular to the lamination may cause significant eddy current loss. By using the SMC, electrical machines can now be designed with three-dimensional (3D) flux paths. Radically different configurations can be exploited for full use of the space, leading to very high power density or power to volume ratio.

The thermal isotropy of SMC material is also a plus for thermal design. The laminated steel sheet has a much lower thermal conductivity in the direction perpendicular to the lamination plane than that within the lamination sheet, so the heat in the laminated cores is almost uniquely transferred at the lamination edges. The SMC cores have heat dissipation in all directions, leading to high flexibility of thermal design.

Because the SMC powder particles are coated with surface insulation and bonding adhesive, the eddy current loss is almost inconsequential, implying that the material can operate with higher frequency. This property fits well with the development of high-power-density electric motors, in which the output power is basically in linear relation with the operational speed or frequency. However, the hysteresis loss of SMC materials is higher than that of electrical steels caused by the particle deformation during pressing, and hence, the SMC has larger total core loss at lower frequency. A proper operational frequency is determined according to overall considerations.

The utilization of this material offers a prospect of low-cost mass-production of electromagnetic devices. Using the matured powder metallurgical techniques, the SMC components can be compacted into the desired shape and dimensions in a die, so further machining is minimized and the manufacturing cost can be greatly reduced.

The most attractive advantage of the material may be its environmental friendliness. Material waste in production is minimized, e.g., less than 3%, and the minimal scrapped material can be recycled back into components or raw material. Furthermore, used SMC motors can be easily crushed for separating and reusing high-value materials like copper, offering much better recyclability than lamination steel machines. In addition, this powder metallurgical process has a lower energy consumption than the punching and stacking processes of laminated cores.

Despite the many advantages mentioned above, SMC materials also have some disadvantages, such as low permeability, low saturation flux density, low mechanical strength, and relatively high core loss at low frequency range. Due to the significant differences in magnetic, mechanical, and thermal properties, a simple replacement of the existing electrical steel cores by SMC cores may result in performance deterioration with very small compensating benefits. Therefore, a large amount of research has been conducted in the past three decades concerning the improvement of the material, property modeling, novel motor topologies, and advanced design optimization of the SMC electrical machines. This article aims to present an overview of the development of high-power-density SMC motors for EVs with focus on 3D flux motors, advanced property modeling, and advanced design optimization techniques.

The rest of the paper is organized as follows. Section 2 summarizes the development of various types of electric motors with SMC cores, with focus on those with 3D magnetic flux path. Section 3 discusses the advanced magnetic property characterization of SMC for SMC motor design and analysis. In Section 4, the advanced design and optimization techniques for SMC electrical machines are summarized. Section 5 discusses the research works from a few material manufacturers and research institutes concerning the improvement of the SMC material properties and manufacturing techniques. Section 6 concludes the article by highlighting the major challenges and key issues for further improving SMC applications in EV motors.

2. Development of SMC Electrical Machines

A number of SMC materials have been developed in the past decades by various material manufacturers, such as Hoganas [40], Horizon Technology [41], and Hitachi Metals, Ltd. [42], and their applications in various types of electric motors have been investigated by different researchers. As mentioned above, the SMC materials have both advantages and disadvantages, and hence, a good design should make full use of the advantages, such as 3D magnetic isotropy and low eddy current loss, while avoiding disadvantages, such as low magnetic permeability. To minimize the effect of low permeability, the favorable type would be permanent magnet (PM) motors. The PM permeability is quite low, with a value slightly higher than air, and its magnetic reluctance of PMs dominates the magnetic circuits, so the effect of low permeability of the SMC core on the motor performance is insignificant. PM motors with 3D magnetic flux paths have been the major research interest of SMC machines.

The University of Newcastle upon Tyne, UK, and Hoganas AB, Sweden, might be the pioneers exploring SMC applications in electrical motors. In 1998, Jack [43] reported their experience with different types of electrical machines with SMC cores, and it appears the largest gains are with the 3D flux machines including combined radial and axial field PM motors, claw pole armature motors, transverse flux motors (TFMs), and combined TFM/claw pole design.

2.1. Axial Field PM Motors with SMC Cores

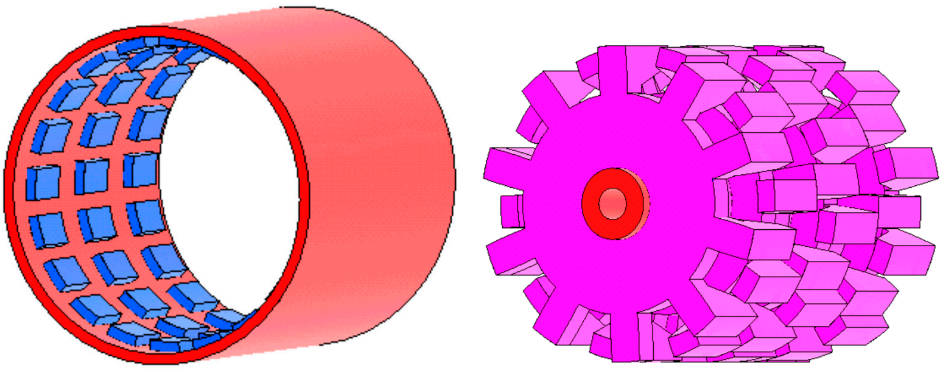
The first SMC machine might be an axial field PM machine with the SMC material ABM100.32 as the core, reported by Persson et al. in 1995 [44]. The slotting of axial field machines normally need spirally-wound laminations, so the use of SMC cores will greatly simplify the production. In 1997, Zhang et al. [45] presented an axial flux PM brushless DC motor in which powder iron metallurgy cores were used to simplify the manufacturing process. In 1998, Profumo et al. [46] designed an axial field interior PM motor in which the rotor construction was feasible only with SMC material. In 2002, Cvetkovski et al. [47] compared two types of stator cores, laminated electrical steel and SMC, for an axial field PM disk motor, and the analysis results were in favor of the SMC core.

In 2007, Liew et al. [48] evaluated the performance of an axial field brushless PM motor with SMC stator core using 3D finite element analysis. In 2014, Maloberti et al. [49] presented the magnetic modeling of an axial field PM motor with an SMC core for EVs. In 2015, Kobler et al. [50] developed an axial motor with an SMC core and ferrite magnets, showing a promising design of low cost, high power density, and no rare-earth PMs. In 2017, Aliyu et al. [51] developed a compact axial field PM motor with concentrated winding and pressed SMC core for reduction of core loss and cost. In 2018, Washington et al. [52] investigated the construction methods of axial flux machines using SMC cores. It has been shown that for small motors, the most appropriate method applies the simplest possible realization, e.g., pressing the stator in a single component. Also in 2018, Nakamura et al. [53] studied a high efficiency axial gap motor with SMC (HB2, Sumitomo Electric Industries, Ltd.) core using the balancing properties of core loss and magnetic permeability. In [54], Asama et al. evaluated the core loss reduction of a disk motor with a C-shaped stator experimentally. Compared with the solid iron core, the SMC (ML28D, Kobe Steel, Ltd.) core can reduce core loss significantly. The conventional lamination steel is not suitable for the C-shaped stator, which has a 3D magnetic flux path.

In 2019, Wei et al. [55] presented a double-stator axial field PM disk motor using an SMC core with emphasis on cogging torque reduction. In 2022, Meier and Strangas [56] presented a high-speed axial field motor with an SMC core, with emphasis on improving cooling design. The SMC enables complex and liquid-tight design for cooling integrated into the motor cores. Also in 2022, Haddad [57] analyzed the core loss of an axial flux PM motor with an SMC core, which is particularly important for high-power-density drives.

2.2. Claw Pole Motors with SMC Cores

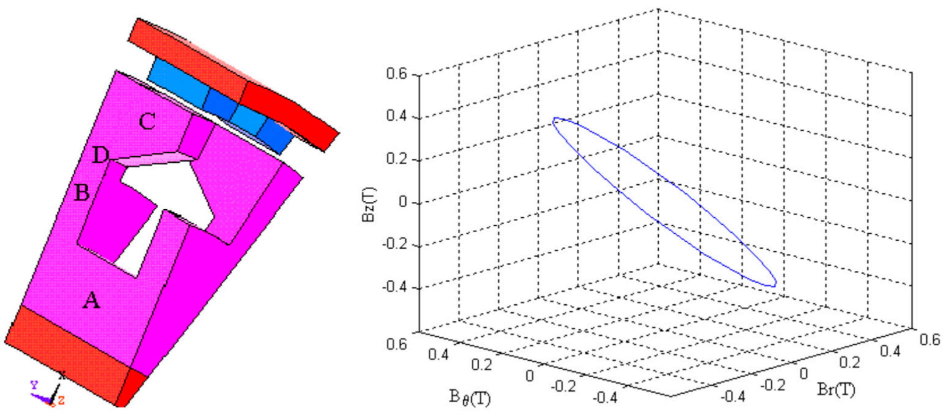
In 1997, Jack et al. [58] presented a PM claw pole machine with an SMC core. It is almost impossible to construct the claw poles using lamination steels, so in general solid steel is used, though it may suffer from significant eddy current loss. The SMC material appears to be an ideal candidate for such structures. In 1998, Guo et al. designed a single phase claw pole PM motor with a Somaloy^{TM} 500 (Hoganas, AB) stator core to investigate the application of SMC materials in electrical machines [59,60]. Based on the single phase motor experience, they developed a three-phase three-stack PM motor with an SMC stator [61,62]. As the magnetic field in claw pole machines is 3D, the core loss was calculated by using an improved model considering the effect of 3D vectorial magnetization [63–65]. Figure 1 shows the magnetically relevant components of the three-phase claw pole motor. The three phases are stacked axially with a circumferential shift of 120 electrical degrees from each other.



(**a**) (**b**)

Figure 1. A three-phase claw pole motor: (**a**) outer rotor with three arrays of PMs on the inner surface of the yoke, and (**b**) three-stack stator cores on a shaft.

Figure 2a illustrates one pole-pitch for magnetic field finite element analysis and Figure 2b plots the flux density locus under no-load condition at Point C of the claw pole when the rotor has rotated by 360 electrical degrees, or two pole-pitches. The flux density is 3D and rotational.



(**a**) (**b**)

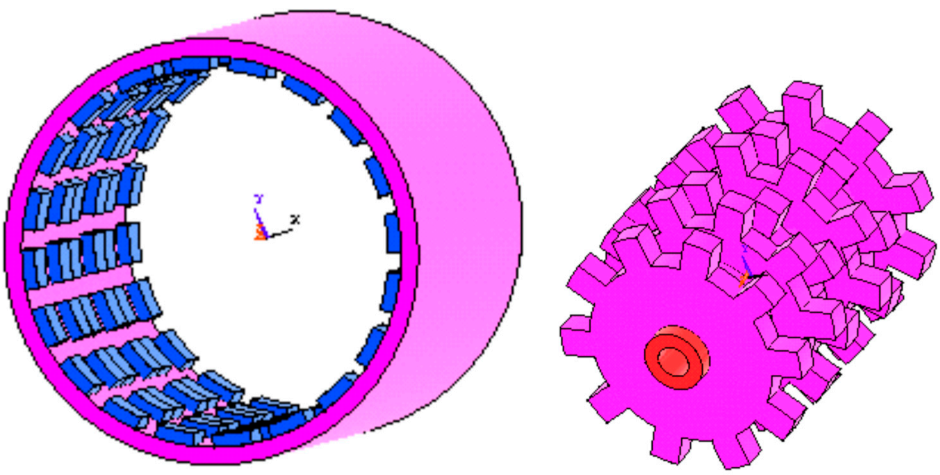
Figure 2. Magnetic field finite element analysis: (**a**) one pole-pitch for numerical analysis, and (**b**) magnetic flux density locus at Point C when the rotor has rotated by 360 electrical degrees.

In 2009, a claw pole PM motor with molded SMC core was developed [66]. The molding technique is a key issue for low cost mass production of SMC machines. Furthermore, their research group has conducted research for improving the performance of claw pole SMC machines, such as cogging torque reduction and robust design optimization, concerning manufacturing tolerance and parameter uncertainty [67–69].

In 2002, Cros and Viarouge [70] developed new structure claw pole machines using the isotropic magnetic property of SMC. In 2004, Qu et al. [71] presented a split-phase claw pole induction motor with SMC cores, which achieved higher efficiency and torque density than normal radial flux induction motors. In 2007, Huang et al. [72] designed a high-speed claw pole PM motor with an SMC core. The core loss distribution was calculated by 3D finite element analysis, and then was directly coupled for thermal analysis. In 2014, Zhang et al. [73] designed a brushless motor with PMs on claw pole rotor. Comparison results showed that with proper design SMC utilization can achieve higher efficiency than using silicon steel. In 2020, Liu et al. [74] proposed a flux reversal claw pole motor with SMC cores, combining the merits of both flux reversal and claw pole machines. In 2021, Du et al. [75] presented a claw pole motor with SMC cores. The study of the SMC preparation process showed that the best magnetic and mechanical properties were achieved through a pressing pressure of 700 MPa and an annealing temperature of 500 °C. In 2022, Chu et al. [76] analyzed a PM claw pole motor with an SMC core, considering the material characteristics over a wide temperature range. Also in 2022, Li, et al. [77] studied a flux reversal claw pole SMC motor for cogging torque minimization.

2.3. Transverse Flux Motors with SMC Cores

The first attempt concerning SMC application in a transverse flux machine (TFM) was reported in 1996 [78]. The TFM prototype achieved very high torque density using a large number of poles and an SMC core. In 2002, Guo et al. developed a TFM with an SMC core for performance comparison with an SMC claw pole motor of similar size [79]. Figure 3 shows the magnetically relevant components of the TFM, and Figure 4 calculates the magnetic flux density loci by using magnetic field finite element analysis. As seen in Figure 4b, the flux density locus at Point B of stator tooth is 3D and rotational. They further improved the design and fabricated a prototype for experimental validation [80,81]. By comparison, the SMC TFM achieved higher specific torque and power than a sample commercial induction machine and a brushless DC servomotor with electrical steel cores.



(**a**) (**b**)

Figure 3. A three-phase transverse flux motor: (**a**) outer rotor with two arrays of PMs per phase on the inner surface of the yoke, and (**b**) three-phase stator cores on a shaft.

In 2013, Doering et al. [82] presented a transverse flux reluctance machine with an SMC core and disc-shaped rotor, in which the determination of core loss in SMC cores is a crucial point. In 2015, Lei et al. [83] conducted multidiscipline analysis and design optimization of

PM TFMs with SMC cores, in which the electromagnetic, thermal, and modal analyses along with the fabrication approach of the cores were studied. In 2016, Liu et al. [84] reported the design considerations for PM SMC TFMs based on a torque equation. They also studied the shifted and unequal-width stator teeth for cogging torque minimization [85].

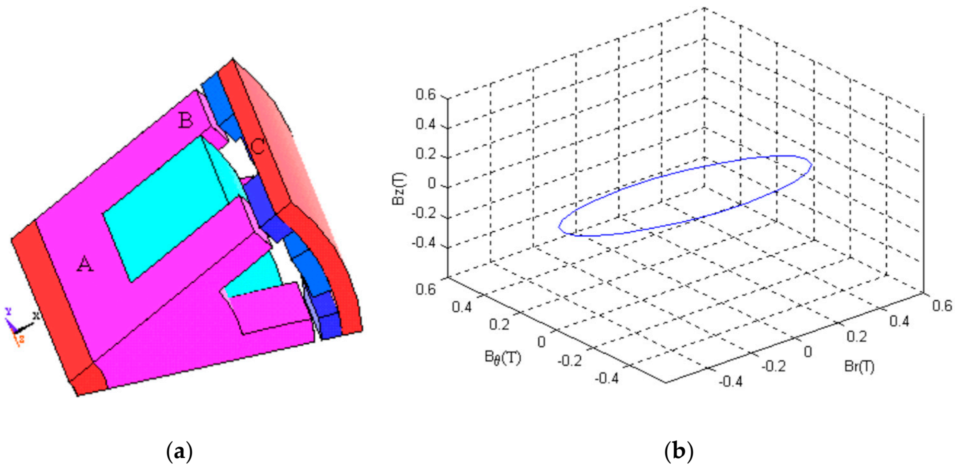


Figure 4. Magnetic field finite element analysis: (**a**) two pole-pitches for numerical analysis, and (**b**) magnetic flux density locus at Point B when the rotor has rotated by 360 electrical degrees.

In 2017, Liu et al. [86] developed a transverse flux flux-switching PM motor with SMC cores and ferrite PMs of low cost design. In 2018, they further developed this flux switching TFM with the capability of linear motion [87]. The adoption of SMC cores enables easy manufacturing of the complex structure of this machine. In 2021, Fu et al. [88] analyzed a linear PM TFM using a nonlinear equivalent magnetic network. The TFM used combined steel and an SMC core to take the advantages of both materials. In 2022, Liu, et al. [89] compared the performance of SMC TFMs with PMs on rotor or stator.

2.4. SMC Machines with Claw Pole/TFM Configuration

The working principles of transverse flux and claw pole motors are quite close since a TFM may be formed by unwrapping the claw poles [43,90]. In 2005, Guo et al. [91] designed a PM claw pole/TFM with SMC core using 3D finite element analysis. In 2008, Lemieux et al. [92] applied SMC with lamellar particles to a claw pole transverse flux machine with hybrid stator made of SMC foot and silicon steel or amorphous C-core. In 2020, Rabenstein et al. [93] designed a wound field TFM using SMC claw poles, which offers advantages in manufacturing. In 2021, Zhang et al. [94] analyzed a claw pole TFM with a hybrid stator core, which achieved improved performance over the SMC core.

2.5. Other Types of SMC Motors

Besides the above-mentioned SMC machines, some other types of 3D magnetic flux machines have been investigated involving the advantages of the 3D isotropic magnetic properties of SMC. In 1999, Jack et al. [95] reported a PM machine with both radial and axial magnets, where the armature must be capable of carrying varying flux in all directions and SMC is an ideal candidate. In 2005, Nord et al. [96] presented a vertical electric motor which has a very different physical architecture from standard machines, and only powdered SMC enables the construction of such 3D magnetic structure. In 2010, Okada et al. [97] presented a PM SMC motor with a 3D magnetic stator, aiming at high efficiency.

In addition, research has also been conducted regarding other types of electric motors using SMC cores, such as radial field PM motors [98–102], universal motors [103,104], induction motors [105,106], and switched reluctance motors [107–110]. With careful design, all types of motors can benefit from the unique properties of SMC.

3. Advanced Magnetic Property Characterization of SMC Materials

3.1. 3D Vectorial Magnetic Properties

The global magnetic permeability or *B* (magnetic flux density)—*H* (magnetic field strength) relation and the associated core loss of the core material are among the fundamental parameters for electric motor design and analysis. As discussed above, the 3D magnetic flux machines will gain the biggest benefits from the material application, so the magnetic properties should be characterized under 3D vectorial magnetization for developing electric motors with 3D flux paths [111]. To measure the 3D vectorial magnetic properties, some 3D magnetic property testers have been developed [112,113], which can generate any desired 3D flux density patterns, such as a 3-D spiral spherical or ellipsoidal locus. However, a pending issue is how to apply the 3D measurement data in motor analysis. Instead, some 2D or quasi-3D magnetic properties have been measured and applied.

3.2. 2D or Quasi-3D Vectorial Magnetic Properties

When only two pairs of excitation coils are excited, the 3D tester can generate a 2D rotating flux density vector, which is equivalent to a 2D magnetic tester. When the 2D vectorial magnetic properties are measured in the three coordinate planes, respectively, the quasi-3D vectorial properties are obtained [114–118]. Similarly, when only one pair of excitation coils are excited, the magnetic properties under one-dimensional (1D) magnetization can be measured [114–119]. Based on the measured 2D and 1D property data on SMC samples, some mathematical models have been developed for predicting the core loss when designing the SMC motors. The results are very satisfactory, e.g., much more accurate predictions than from using conventional models [120–122].

3.3. Challenges of Vectorial Magnetic Property Characterization

Although applying vectorial magnetic property data and models to developing SMC electric motors with 3D rotational magnetization has been expected, the 3D or 2D property data are generally not available. Only a few research groups have the 3D or 2D magnetic property testers, and the 2D/3D measurements are not yet standardized. Therefore, the available magnetic property data are basically obtained under 1D alternating magnetic fluxes, which are measured using a ring sample or the Epstein frame. Some researchers have applied approximate models to consider the effect of rotational magnetization. For example, Huang et al. considered the core loss as having two parts, each of which is caused by a component of the flux density, e.g., the major or minor axis of an elliptical locus [123]. The method can consider somewhat the effect at low flux density range, but it becomes invalid at the saturation level.

Another challenge concerns the modeling of magnetic permeability or the *B*-*H* relations. Under 2D/3D vectorial magnetization, the permeability relating the *B* and *H* becomes a full 2D or 3D matrix with both diagonal and off-diagonal elements [124–127]. While the elements can be easily determined based on the measured 2D/3D properties, their application in magnetic field analysis is still very difficult, particularly the 3D case.

Besides the magnetization pattern, magnitude, and frequency, the magnetic properties are also affected by many other factors, such as operational temperature, mechanical stress, DC bias of magnetic flux, and magnetostriction. Therefore, for high performance motor design and analysis, the property characterization should take the effects of multi-physics factors into account [128–131].

4. Advanced Techniques for SMC Motor Design and Optimization

As discussed above, the SMC material has both advantages and disadvantages, and a direct replacement of the conventional silicon steel by the SMC core might lead to performance deterioration with little compensating benefit. Then a good design should fully take the advantages while minimizing the effects of disadvantages. A typical electric drive system consists of a few components like the electric motor, power electronic converter and controller, and traditionally the components are designed and optimized separately.

Assembling the individually optimized components will not necessary lead to an optimized system. Therefore, to achieve the system-level optimization, the components should be optimized together [132–138]. This is very challenging due to the multi-discipline and complex nature and interactions among components with manufacturing and operation uncertainty.

For the optimization of a drive system, the most straightforward approach is to take all the design parameters of different components as the design variable, but this would cause extremely high computation cost due to the very large number of parameters and complex models. To overcome this problem, the multi-level multi-disciplinary techniques may be applied [139–142]. The design variables may be divided into several levels according to their sensitivity to the optimization objectives, e.g., highly significant, significant and non-significant parameters.

There are many uncertainties during the electric motor production and operation like manufacturing tolerance and parameter variation, which may greatly affect the motor performance and reliability and should be taken into account [143]. In 2012, Lei, et al. [69] applied the six sigma based robust optimization to a PM TFM with an SMC core. The reliability and robust level of the motor drive system are greatly improved and the failure probability is much reduced. They further studied the PM SMC motors for high quality manufacturing, particularly batch production, using the six sigma (DFSS) approach design [144–146]. In 2018, they conducted the robust optimization of a PM claw pole motor with an SMC core by simultaneously optimizing the design variables and tolerance based on the DFSS [69]. The tolerance optimization achieves more design freedom to balance motor performance, operation reliability, and manufacturing cost. Furthermore, they have improved the design optimization of the SMC motors by combining the robust, multi-level, multi-disciplinary, and multi-objective approaches, and very promising results have been achieved [147–149].

5. Development of SMC Materials

5.1. Improvement of SMC Material Properties

Besides the above-mentioned researches concerning the advanced design of SMC electric motors, a few manufacturers and institutes have worked on the improvement of the material properties and manufacturing techniques [40–42]. Among them, Höganäs is one of the most famous SMC material manufacturers that started the study and manufacturing of SMC materials in the early 1990s, in collaboration with the University of Newcastle upon Tyne. Somaloy® is Höganäs' trademark for SMC powders with unique 3D flux properties. The Somaloy product family includes three groups: 1P, 3P, and 5P, with different performance levels (P). Somaloy 1P is the base level material, and maximum heat treated temperature (Temp HT max) is 550 °C with air atmosphere. Somaloy 3P has the highest mechanical strength, and its Temp HT max is 550 °C with steam treatment. Somaloy 5P has the lowest hysteresis losses, and its Temp HT max is 650 °C with inert atmosphere [40]. Figure 5 shows the comparison in terms of mechanical strength and magnetic losses of these three groups.

SMC materials are usually prepared by traditional powder metallurgy processing. The general steps are first to insulate the surface of particle-scale metal magnetic powder, next to evenly mix the insulated particles with organic or inorganic binders, followed by press molding, and finally the annealing at a certain temperature to eliminate internal stress and improve magnetic permeability. Throughout the process, the core technology of soft magnetic composite materials includes the coating, pressing, and annealing processes [150]. The coating process covers insulating materials in the form of single particles to build high resistance grain boundaries to reduce the eddy current loss of the material. The currently developed technologies include mechanical milling, surface oxidation, microwave treatment, etc. [151,152]. The pressing process improves the magnetic permeability and saturation magnetic flux density by turning the insulating-coated particle powder into a high-density material under high pressure. The pressing pressure is usually lower than 1000 MPa. If the particles are small or the hardness of the insulating layer material is high, the pressing pressure needs to be increased, up to 3000 MPa [153]. High pressure pressing can also cause dislocations inside the material and increase the internal stress, thus increasing the coercivity of the material [154]. At this time, it is necessary to eliminate the internal stress of the material through annealing processing to increase the magnetic permeability and thus reduce the coercivity. Moreover, SMC materials need to be annealed between 400-800°C, eliminating the internal stress inside the material while protecting the insulating layer from damage to keep the high resistivity. At the same time, the mechanical strength of the material can be improved through annealing treatment.

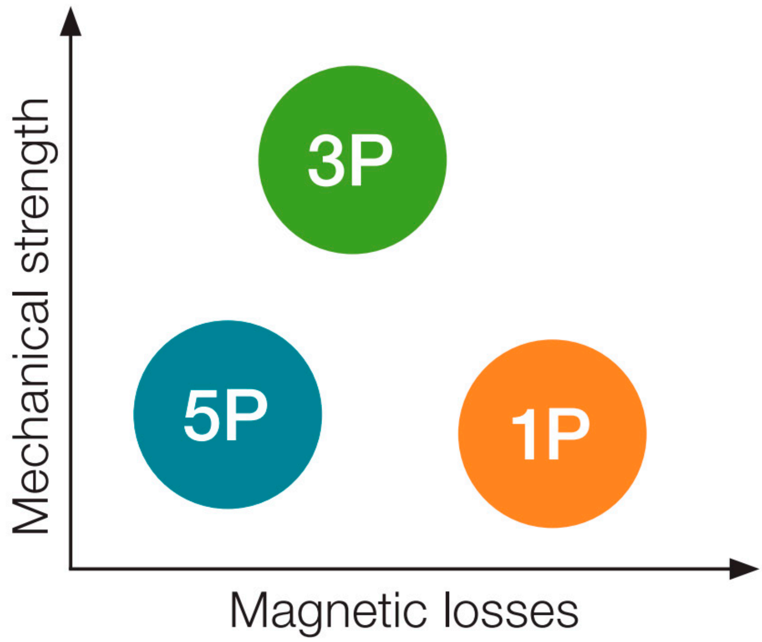


Figure 5. Mechanical strength and magnetic losses of three groups of Höganäs Somaloy SMC materials.

The magnetic properties, such as the B-H relations and the core loss curves against magnetic flux density and frequency, as well as mechanical and thermal properties, are usually provided by the material manufacturers. For the detailed properties of a particular SMC material, the relevant data may be found in the relevant websites [40–42].

It should be noted that the magnetic properties from the material suppliers are all measured with 1D alternating magnetic flux. However, for the electrical machines, the power loss caused by the 2D or 3D rotating fields may be very different from that caused by the 1D alternating fields [117,155]. Figure 6 illustrates the measured alternating and 2D circularly rotational core losses of a soft magnetic composite (SMC) block sample [155]. Results show that the rotational core losses relative to two cases are very different. At low to mid-range flux density, the rotational core loss approximately equals double of its alternating counterpart. At the saturation level, however, the rotational core loss decreases quickly to the level well below the alternating core loss, which continues to decrease with the rising flux density. Therefore, new and proper models should be investigated for calculating the core loss.

Although significant improvements of the SMC properties have been achieved in the last three decades through the continuing effects of various material manufacturers and research institutes, the SMC materials still have lower magnetic permeability, mechanical strength, and thermal conductivity, as well as a higher total core loss at lower frequency compared to traditional silicon steels. Therefore, it is crucial to conduct the system-level design of electrical motors by fully utilizing material advantages, such as 3D magnetic and thermal isotropies and lower total core loss at higher frequency, as well as low-cost green manufacturing.

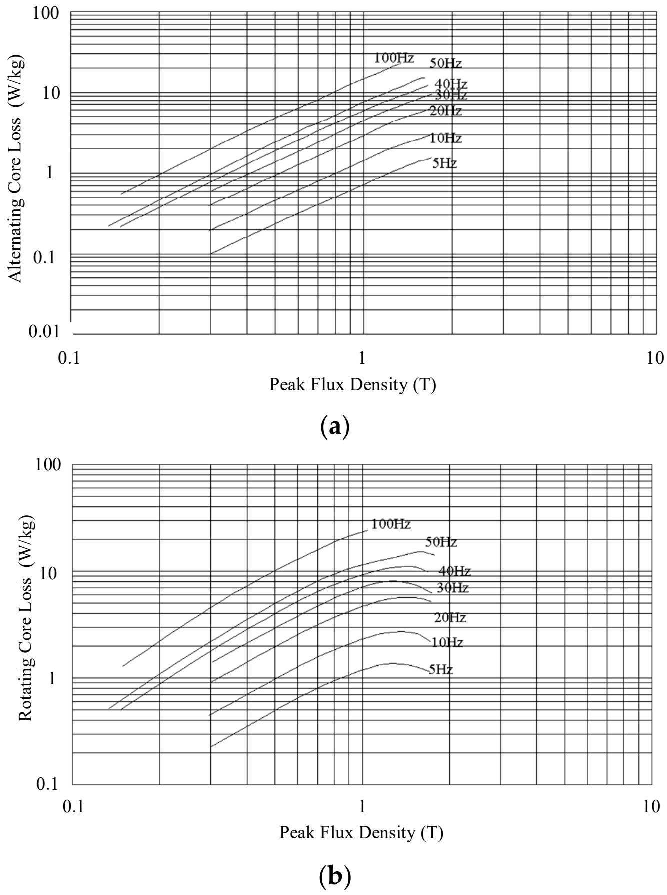


Figure 6. Measured core losses of SMC sample: (**a**) with alternating flux, and (**b**) with circularly rotating flux [156].

5.2. Cost of SMC Materials and Motors

The SMC materials are expected to be very cheap, but their cost is currently several times higher than that of conventional electrical steels. The major reason is that the production of SMC materials is still at a very low volume as their applications are currently focused only in situations where electrical steels are not appropriate, e.g., 3D magnetic flux electrical motors. Despite this disadvantage, the overall cost of an SMC electric motor drive system with proper design can be lower than for corresponding silicon steel motors. For example, the motor size and weight can be effectively reduced by using SMC cores, the machining demand is reduced during the motor manufacturing, and the scrap rate is low during motor production [156].

5.3. Comparison of Electrical Motors with SMC and Conventional Electrical Steel Cores

As described in Section 2, various types of electric motors have been developed using SMC cores. The results are very promising, e.g., the SMC motors can achieve better overall performance than their counterparts with electrical steel cores. Some direct comparative studies have also been conducted to reveal the benefits of using SMC cores over electrical steel cores. In 2006, Hamler et al. [157] compared the performance of a permanent magnet synchronous motor with a stator made of the classical laminated silicon iron sheets and the SMC material. With the same stator core shape, the SMC motor can achieve a slightly better performance than the laminated one using the 3D magnetic flux topology, and at a slightly lower cost. In 2017, Kim et al. [158] carried out a comparative study on axial-field PM motors with an SMC core and electrical steel core. It was found that the motor performance with the SMC core had superior performance to that with the laminated core in a high-frequency region. In 2018, Lim et al. [159] compared the performances of an SMC surface mounted PM machine with embedded stator end-winding versus a corresponding conventional electrical steel stator design with the same overall axial length. The SMC machine with embedded stator end-windings could achieve a higher power density than the corresponding silicon steel machine of an equal volume. In 2023, Wang, et al. [160] compared the performance of tubular flux-switching PM machines with SMC core and SMC-electrical steel hybrid core. The respective advantages of both SMC and electrical steel are used for improving the motor thrust force and reducing core loss.

6. Discussions and Conclusions

This paper presents a comprehensive review of the development of an electric motor with SMC cores for electric drive, focusing on high power density, high reliability, and system optimal performance. The biggest benefits from the SMC application concern those motors with 3D magnetic flux topologies and powder metallurgical manufacturing. Appropriate magnetic property modeling of the SMC material under 3D vectorial magnetization and multi-level multi-discipline multi-objective robust design optimization techniques should be applied for designing high performance motor drives.

Although many achievements have been made, there are still a number of challenging problems to be solved. The data of magnetic properties under vectorial magnetization and their accurate and effective modeling are still far below the requirement. The manufacturing techniques need to be improved for stable compaction with uniform mass density and desired tolerance.

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