Soft magnetic composites: recent advancements in the technology

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Soft magnetic composites allow for revolutionized designs of electromagnetic devices to aid in improved efficiency and reduced weight and costs, without sacrificing magnetic performance. Electrically insulated core powder are formed into toroid shapes and tested for core loss and magnetic permeability, which are desired to be minimized and maximized, respectively. Ferromagnetic powder has shown the most potential as core materials, however nanocrystalline materials are highly resistive and amorphous materials have benefits of very low coercivities. Likewise, organic and inorganic coating materials have been explored for the reduction of eddy currents to improve overall core losses at higher frequencies. The balance between properties is of the utmost concern for SMC applications.

Our world is focused on making devices faster, lighter, and more innovative; why should electric motors be any different? Electric motors convert electrical energy to mechanical energy using direct current (DC) from stored energy, say in batteries, or alternating current (AC) from generators or the power grid. They are found in electric cars, small house hold appliances, industrial fans and pumps, machine tools, as well as in large ships and planes for propulsion. Continuous research on soft magnetic composites (SMCs) has shown their vast potential for DC and AC applications that improve the magnetic induction of core materials at low to high applied frequencies by allowing new innovative designs developed by engineers. SMCs are comprised of electrically insulated ferromagnetic powder that allow for several worthy advantages when particle size, shape, and microstructure are optimized. These unique properties include magnetic and thermal isotropy, high magnetic permeability, low coercivity, high Curie temperatures, and low total core losses [1]. In addition, the nature of powder metallurgy allows customers to reduce the material consumption with a smaller motor design or obtain higher power from similar dimensions as their current electric motors, which opens up an enormous market for electromagnetic devices [2]. These components have the ability to bridge the gap between traditional laminated steel cores limited to frequencies of a few hundred Hz and ferrite cores limited to above a few MHz. The elimination of failure/overheating of motors often because of eddy current buildup resulting from poor insulation of ferromagnetic layers can be completed with SMC materials [3].

A well-known and highly referenced review on soft magnetic composite materials was published by H. Shokrollahi and K. Janghorban in 2007 [1], which highlights much of the theory behind these material systems. The review article presented here focusses on the most recent documented research on SMCs and the variations in core and coating materials. During the last decade, studies have focused on increasing magnetic permeability and lowering core losses of SMCs to result in higher frequency applications, nominally from 400 Hz to a few kHz [4–14]. A high magnetic induction and low coercivity are necessary to increase permeability and efficiency, obtained by having minimal structural boundaries so that magnetic domains can move easily and reduce the required energy input to obtain similar magnetic responses. Lowering core losses is completed by reducing hysteresis and eddy current losses. This is obtained by having the least amount of nonmagnetic inclusions and a high electrical resistivity, developed by using a high purity ferromagnetic powder as the core material and a thermally stable, electrically resistive coating material, respectively. However, the addition of a nonmagnetic

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coating layer will greatly reduce the overall magnetic permeability, which yields a problematic balance of properties. Various applications of soft magnetic composites have been recently studied, including two types of permanent magnet synchronous motors – transverse flux motor (Fig. 1) and claw pole motor [15–17], two types of crankshaft induction hardening coils – eloterm (rotational) and clamshell (non-rotational) [9,18,19], and brushless DC motors [20,21], to name a slight few.

**Processing steps**
The processing methods to form SMCs often follow conventional powder metallurgy techniques, such as milling or mixing of metal powder potentially with alloying elements, compacting, curing, and secondary operations, as depicted in Fig. 2. Milling of various elemental powder allows for the development of mechanically alloyed core materials, often annealed to control grain size and increase magnetic permeability [6]. Smaller grain sizes, nominally nanocrystalline materials have very high coercivity ($H_C > 1000$ Am$^{-1}$) and are less compressible as compared to large grained-ferrous alloys ($< 10$ Am$^{-1}$) [22]. The ferromagnetic powder then must be coated with an electrically resistive material to reduce large eddy current buildup and confine them within individual particles. The procedure for coating powder has been a large area of research, including surface oxidation [23,24], microwave treatment [25], sol-gel method [26–28], and microemulsion method [29,30]. Coating materials that bond well to itself and the ferrous core powder have great potential for improving density and mechanical strength of SMCs.

Coated particles are compacted to form the desired shape and obtain high green densities, necessary for maximum permeability and saturation induction. Typical compaction pressures are below 1 GPa; however, materials that do not compress well because of very small grain sizes or hard coating materials may require higher pressures, even up to 3 GPa [6,31,32]. Even small amounts of cold working will increase the coercivity of a material by inducing dislocations and increasing microstrain [33]. Therefore, iron-based SMC materials should be cured between 570 and 775 °C to properly relieve the stress and dislocations brought on by compaction. However, such a low temperature heat treatment does not allow for sintering of particles to improve density and mechanical strength, often necessary for handling components during assembly and winding of motor cores. Curing is necessary to preserve the coating layer so that no metal-on-metal contact points are found and in-particle eddy currents can be obtained as opposed to inter-particle eddy currents [1]. A unique approach of “double press–double cure” (2P2C) developed by Narasimhan et al. is capable of achieving high densities (>7.5 g/cm$^3$) using warm (80 °C) compaction between 700 and 830 MPa and multiple curing and compacting steps [34]. This technique initially compacts the powder, then cures at 400 °C for 1 h, then represses the compacts under the same conditions, and finishes with a second curing step of 450 °C to insure minimal porosity and maximum density, without diminishing the coating material (proprietary in this study).

**Material selection**
By and large, selecting the proper material for any application is of the utmost importance. SMCs require materials with superb soft magnetic properties to be functional at the desired frequency and possess the mechanical integrity to be handled in a manufacturing facility and perform at high speeds. The soft magnetic properties of interest include high magnetic permeability (high magnetic saturation and low coercivity), which are obtained by the least amount of nonmagnetic inclusions. A great comparison of magnetic properties for typical electrical machine cores is presented for various lamination alloys, an amorphous iron, and a soft magnetic composite, in which each system possesses a leg up on their competition in one way or another [35]. Without a doubt, SMCs allow for the highest electrical resistivity using organic or inorganic coatings because of the electrical insulation between particles, ultimately
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