OPTIMAL USE OF SOFT MAGNETIC POWDER COMPOSITES (SMC) IN ELECTRIC MACHINES

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ABSTRACT
Insulated pure iron powder or so called “Soft Magnetic Composite (SMC)” is finding more use in electric motor applications especially in motors operating at high frequency with a three-dimensional magnetic flux path. With increasing values of operating frequency the use of SMC can contribute to a substantial decrease of specific core losses of the machine, increasing at the same time its total efficiency. In contrast to laminated cores, the manufacturing process of soft magnetic composites does not influence their final magnetic properties. These properties are homogenous and do not change after assembly of the motor. New SMC materials can outperform current laminated steel materials when measurements are done in the same conditions with similar samples. Many prejudices existing about the magnetic properties of SMC can thus be eliminated or attenuated if we respect its optimal use in adequate applications.

INTRODUCTION
Continual advances in the area of e-mobility and high power density electric motors bring new challenges to the traditional laminated motor construction. It is well known that traditional laminated motor construction is limited to 2D magnetic flux to minimize losses in the direction perpendicular to the steel lamination. Because SMC has a 3D magnetic flux path, it is an ideal solution for applications such as transverse flux motors.

Also, in high frequency alternating magnetic fields, SMC materials act as an insulator to the eddy current and thus provide overall low iron losses. The optimal use of SMC can increase the power density of the electric machine. For electrical steel based asynchronous and transversal flux machines the power density, expressing power which can be performed by a certain size of the motor, can reach values of 0,1 - 7,0 kW/dm³. According to the own expertise these values can be substantially increased by the use of SMC in transversal flux machines and by optimization of design. Powder metallurgical manufacture has the singular ability to produce near net shaped products (gear box parts, motor parts) for the automobile
industry. SMC materials coupled with the P/M production process open new possibilities in the design and manufacture of parts for electrical applications.

These properties can be improved or optimized by the right choice and appropriate use of the soft magnetic material.

**ELECTRIC MACHINES – STATE OF THE ART**

The majority of electric machines are based on the use of electrical steels. In order to improve the efficiency of the machine it is necessary to lower all inherent losses like iron-losses, magnetising losses, friction losses and windage losses. The iron-losses can be defined as a sum of the linear frequency dependent hysteresis loss, eddy-current loss - with the square of frequency increasing value and of the anomalous loss - depending amongst others on the structure of the material. The classical eddy-current loss for thin sheet is determined by the following equation:

\[
P_e = \frac{(\pi B f d)^2}{6 \rho_m \rho_e}, \text{[W/kg]}\]

where:

\(B\) – induction [T], \(f\) – frequency [Hz], \(d\) – thickness [m], \(\rho_m\) – density [kg/m\(^3\)], \(\rho_e\) – specific electric resistivity [\(\Omega\)m].

Thus, the way to reduce the eddy-current losses of the material at defined frequencies is by decreasing the sheet thickness and increasing specific electric resistivity. This can be achieved for example by alloying with silicon.

The laminated cores from Si-alloyed electrical steels are the most widely used solution to meet these requirements, see Figure 1.

**Figure 1:** Laminated motor cores.\(^2\)
INFLUENCE OF THE MANUFACTURING PROCESS ON MAGNETIC PROPERTIES

It is a matter of common knowledge that the magnetic properties of stators or rotors depend strongly on their manufacturing process.\(^3\)

In the case of electrical steels this process includes punching, various assembling methods of laminations (automatic stacking, riveting, welding…) and pressing into the motor frame. These processing steps cause an interior deformation of the material resulting in deterioration of magnetic properties. An example for this deterioration after various steps of manufacturing process is presented in Figure 2.

It is a challenge for designers of electric machines to correlate the magnetic properties measured on an Epstein sample, containing only strips in longitudinal and transversal direction and ignoring the negative influence of the manufacturing process on these properties, in a real motor. Various correction factors for different types of electric machines are applied as a solution to this problem.

With SMC prototyping, magnetic properties are measured on toroidal samples considering all magnetising directions in the plane, minimizing the need for correlation between test samples and real motors. The magnetic components have a final shape after curing and there is no additional manufacturing process negatively influencing their magnetic properties.

![Figure 2: Influence of manufacturing steps on the magnetic properties of the electric motor; example: asynchronous motor 1.1 kW; magnetizing behaviour (a), specific core loss (b).\(^3\)](image)
MAGNETIC PROPERTIES OF SMC IN COMPARISON WITH ELECTRICAL STEELS

To ensure a fair comparison between the magnetic properties of electrical steels and SMC, the measurements should be done on samples with the same geometry. The influence of geometry on magnetic properties of electrical steel grade M330-35A is presented in Figure 3. Additional measurements on different grades with thicknesses of 0,20-0,35 mm confirm this tendency.

Figure 3: Influence of sample geometry (Epstein-sample vs. toroidal sample OD=55 mm, ID=45 mm, H=5 mm) on the magnetizing behaviour (a) and specific core loss vs. frequency of electrical steel grade M330-35A (b).

The distribution of magnetic losses in SMC cores deviates from the behaviour in laminated cores because of a different structure of ferromagnetic material components. The hysteresis losses of SMC are higher and the eddy-current losses result from the internal losses within the particles. This general characteristic is illustrated in Figure 4a.5

The frequency value of the transition point depends on the nominal thickness of comparable electrical steel and can vary for the typical commercial grades between 500 Hz…1500 Hz. So, the application of SMC becomes interesting for machines operating at elevated frequency or for machines with a substantial amount of higher harmonics. A comparison between the specific core losses at various frequency values for selected electrical steel grades and SMC grades is shown in Figure 4b.
Figure 4: Frequency behaviour of SMC and electrical steels; general view (a) and comparison of selected electrical steel grades with SMC grades (b); all values measured on toroidal samples.

Figure 5: Microstructure of soft magnetic powder composites: illustration of iron powder particles with insulation layer (a); typical microstructure after compacting and curing (b).
SMC consist of high purity water atomised iron powder with a continuous surface insulation layer (Figure 5a). This electrical insulation reduces the eddy-current losses in the material. Because of the typical structure with pores (Figure 5a) the permeability of SMC materials is generally lower than the permeability of electrical steels. The magnetizing behaviour ($J$ vs. $H$) and the permeability were determined as well. The designers however have to decide whether this fact is relevant for the calculated magnetic circuit because of the resulting ratio between the iron path and the air gap. Figure 6 shows the permeability of tested materials “as measured” and under consideration of an air gap (1 mm) according to the simplified equation:  

$$ \mu^* = \frac{1}{\frac{\mu_r}{\mu_f} + \frac{l_L}{l_{Fe}}} $$

$\mu^*$ - overall permeability of the magnetic circuit, $\mu_r$ – relative permeability of soft magnetic material, $l_L$ – length of air gap, $l_{Fe}$ – length of (soft) magnetic path (e.g. Fe).

According to this equation the difference between the permeability of SMC and of electrical steel becomes negligible with increasing length of air gap. For typical transversal flux motors and machines with permanent magnet excitation the resulting air gap is substantially higher then for e.g. asynchronous machines, decreasing the significance of permeability of various soft magnetic materials.

![Figure 6: Comparison of permeability of selected electrical steels and SMC (SIRON® S manufactured by PMG Füssen GmbH) as measured (a) and under consideration of 1 mm air gap (b).](image)
MANUFACTURING PROCESS OF SMC COMPONENTS

The manufacturing process of SMC components is presented in Figure 7.

Manufacturing of magnetic components occurs in conventional powder metal processing which is well established for high volume manufacturing of net shape or near net shape complex products. SMC utilise a processing sequence as follow:

⇒ Mixing of powder with lubricant or binder
⇒ Compacting
⇒ Curing at relatively low temperatures (200 – 650°C)

Process parameters influencing the magnetic properties include compaction tonnage and, curing conditions (temperature and time). Cross-sectional area of the component must also be carefully accounted for.

For special applications requiring high strength after the curing process or good machinability (e.g. for prototyping), a special iron-resin material system (SIRON®S…b) was developed. Additionally, the magnetic properties of these materials (Table I) are very stable and suffer little change from subsequent machining processes, which makes this material ideal for manufacturing production prototypes using machined blanks.

Figure 7: Manufacturing process of SMC components (source: PMG Füssen GmbH).

Using this manufacturing process makes it possible to form even complicated three-dimensional core shapes for various types of transversal flux motors like e.g. axial flux motors, pancake core motors, claw pole motors (Figure 8).
Table I: Some relevant properties of SMC for the design of electric machines

<table>
<thead>
<tr>
<th>Property</th>
<th>unit</th>
<th>SIRON®S280b</th>
<th>SIRON®S300b</th>
<th>SIRON®S360</th>
<th>SIRON®S400b</th>
<th>SIRON®S720</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ability for machining</td>
<td></td>
<td>✔</td>
<td>✔</td>
<td>-</td>
<td>✔</td>
<td>-</td>
</tr>
<tr>
<td>TRS</td>
<td>MPa</td>
<td>90</td>
<td>120</td>
<td>40</td>
<td>120</td>
<td>120</td>
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<tr>
<td>$B$ at 4.000A/m</td>
<td>T</td>
<td>1.06</td>
<td>1.15</td>
<td>1.19</td>
<td>1.35</td>
<td>1.35</td>
</tr>
<tr>
<td>$B$ at 10.000A/m</td>
<td>T</td>
<td>1.5</td>
<td>1.52</td>
<td>1.53</td>
<td>1.64</td>
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<tr>
<td>$H_c$ (DC)</td>
<td>A/m</td>
<td>138</td>
<td>335</td>
<td>110</td>
<td>235</td>
<td>235</td>
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<tr>
<td>$μ_{max}$</td>
<td></td>
<td>-</td>
<td>283</td>
<td>312</td>
<td>366</td>
<td>400</td>
</tr>
<tr>
<td>Iron loss (10000A/m) DC</td>
<td>mJ/kg</td>
<td>295</td>
<td>290</td>
<td>58</td>
<td>155</td>
<td>155</td>
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<tr>
<td>Core loss at 1T</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>100Hz</td>
<td>W/kg</td>
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<td>6</td>
<td>7</td>
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<td>830</td>
<td>945</td>
<td>722</td>
<td>1100</td>
<td>1253</td>
</tr>
</tbody>
</table>

OPTIMAL USE OF SOFT MAGNETIC POWDER COMPOSITES

In comparison with widely used electrical steels, SMC have advantages making them suitable for special constructions of electric machines. These advantages are:

- High power density by 3D magnetic flux conduction
- Lower core losses at elevated frequencies compared with electrical steel
- Good formability; complex shapes can be directly compacted without destroying the material structure and resulting deterioration of magnetic properties.

Since the magnetic cores get their final shape after compacting and their final magnetic and mechanical properties after curing, they can be immediately wound with wires and assembled into the motor frame. This enables the magnetic core manufacturer to scale the design, and simplify both the core winding geometry, and the motor manufacturing process.

Figure 8: SMC components for electric applications (products of PMG Füssen GmbH).
An example for the use of SMC in a stator of an axial flux motor is presented in Figure 9.

The isotropic nature of the SMC material combined with the net shaping possibilities allow us to introduce new three-dimensional design solutions with minimal iron losses and optimized copper winding. The ongoing development in the area of soft magnetic composites proceeds as follows:

- improvement of magnetising behaviour
- improvement of saturation polarisation
- shifting of transition point of the eddy-current loss (see Figure 4) to lower the values of frequency
- optimal choice of application according to the relevance of permeability (see Figure 6)
- improvement of mechanical strength.

These improvements are accomplished through optimisation of the compacting and curing process as well as the addition of special binders or lubricants.

![Stator of an axial flux motor (DYNAX® from Compact Dynamic GmbH) with SIRON® S300b components (PMG Füssen GmbH).]

**Figure 9**: Stator of an axial flux motor (DYNAX® from Compact Dynamic GmbH) with SIRON® S300b components (PMG Füssen GmbH).

**CONCLUSIONS**

Electrical machines with three-dimensional magnetic flux are needed for high efficiency motor applications. At the same time, new applications requiring high operating frequencies are becoming more available. Soft magnetic powder composites are the upcoming development in the powder metallurgy offering optimal magnetic properties at elevated frequencies and contributing to the increase of the power density and to miniaturization of electric machines. This makes SMC perfect for applications with limited space e.g. in the automotive industry, robotics or selected home appliances.

**REFERENCES**


