Recent Development of Soft Magnetic Composite Materials and its Application

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***Abstract*—This paper explores recent material development for Soft Magnetic Composites (SMC) which are based on pure iron metal powders combined with inorganic resistive coatings. SMC components are manufactured by compaction in a shaped tool followed by heat-treatment of the component for stress relaxation and to reach optimal magnetic and mechanical performance. The recently developed Somaloy® 5P SMC materials are presented and compared to former technology. The unique combination of material properties and manufacturing process is here concluded to enable possibilities to realize compact and efficient high-frequency electromagnets, a technique that can be an interesting opportunity for large volume, cost efficient magnetic bearings and bearingless applications.**

I. INTRODUCTION

Soft magnetic components are used in electromagnets to provide a well-defined, efficient magnetic flux path that enables high performance of the application. Iron, cobalt and nickel are the main ferromagnetic base elements. Iron is the most common and also the least expensive of these three. The magnetic properties are focused to the base elements and the performance is to a large extent ruled by the purity and cleanness of the final engineering material.

The total losses connected to the magnetization are commonly subdivided into hysteresis-, eddy current- and the remaining anomalous losses. Eddy current losses are frequency dependent and proportional to the materials electric resistivity but depends also on the cross-sectional dimensions of the component perpendicular to the magnetic flux path. Electrically isolated steel-sheet lamination is the predominant solution to the eddy current problem.

The limitations of the lamination technique is the two-dimensional structure that results in sharp edge rectangular cross-sections of the soft magnetic core that also rules the process of winding and do often require quite thick bobbins to avoid short-circuits between the winding and the core. Another restriction is the cost for making thin laminations as the rolling process will be less productive and technically difficult when the lamina thickness decreases. Punching of thin laminas is also an area of extended challenges.

The idea to use metal particles as soft magnetic material for electromagnetic cores is not new; already in 1886 Fritts [1] applied for a patent of a generator using e.g. gutta-percha filled with iron particles as core material. A ‘newborn’ interest in SMC materials for machines started in the 1990s followed by intense material development to improve the competiveness of SMC. This development is driven by development of switch mode power supplies and demands on higher frequencies still providing commercial cost efficiency in volume applications. Typical development areas are high efficient traction drives for electric vehicles, other automotive applications forced by extended electrification mainly driven by efficiency demands, home appliances like HVAC pump drives and many other applications.

The introduction of SMC is, in the majority of cases, connected to new development since many traditional solutions based on rather low-cost laminations are difficult to challenge with the more engineered and also somewhat more costly SMC technology when just compared core-to-core in a direct replacement situation.

The SMC components will show a unique property profile and a successful SMC application should of course then make the best use of these special values. It can be of great help to focus on some simple rules to more efficiently judge the applicability of SMC to a specific application. At least the following five points are recommended to be considered when approaching SMC as core material for an electromagnetic application:

- The application works at higher frequencies and demands lowest losses
- The aim is efficient volume production
- Compact design is rewarded
- There is a value in savings of other components
- When it may be beneficial to integrate functionality by other geometrical features direct in the core body

The list implies that SMCs are not simply just new materials but also to a large extent add values that are uniquely connected to the forming and production process of components and systems. These aspects do also indicate the requirement of special competences that should be present to ensure a successful development work with SMC. The electric application engineer is advised to gain some understanding of the forming and production process of SMC powder components since this actually can be a critical point of the application development.

II. MODERN SOFT MAGNETIC COMPOSITE MATERIALS

The first ‘modern’ SMC materials were also based on an organic matrix that bonds the particles and also provide the resistive coating. The resistive coating creates the bulk resistivity of the material. The organic matrix can positively supply quite a high mechanical strength and resistance to eddy currents in the SMC components. However, the disadvantage

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is the limited heat-treatment temperatures that are restricted to about 200-300°C. This temperature level is not enough to bring full stress relaxation of the deformed powder particles and will unconditionally result in relatively high hysteresis losses then taking out a part of the effect of the typically low eddy current losses.

A more attractive alternative is to use an inorganic particle surface coating system that can stand high temperatures and that allows for optimal relaxation of the particle for minimal hysteresis losses.

Another important condition is the lubrication during the press and compaction process. There are mainly two methods available; die wall lubrication (DWL) adding lubricant direct to the walls of the tool and/or internal lubrication by mixing a lubricant with the magnetic powder recognized as a premix.

The main benefits of using a premix is the much higher productivity and less variation in final properties of the component compared to DWL. It is also very important that the internal lubricant will add to preserve the resistivity of the particle coating else the eddy current protection will be lost and losses will increase.

Saturation induction of SMCs is quite high and the internal in-particle eddy current losses are significantly lower due to the smaller particle size, typically 5-400µm compared to the thickness of the steel sheet laminations of normally 100-1000µm. As a result of the isolating coating layer, the SMCs have distributed air gaps leading to lower permeability shown in Fig.1.

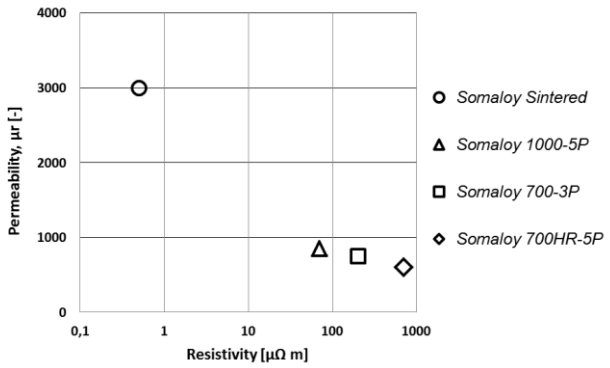


Fig.1 Relation of permeability to resistivity for a selection of Somaloy SMC grades with similar particle size.

The high pressures applied to the powder in the press-tool will deform the particles and will give high density. The softer the particle is the less effort is required to achieve high density. Alloyed or badly conditioned as well as small particles will be more difficult to deform into high densities. High quality SMC powder products have very good compressibility. Typical forming pressures for SMCs are in the range of 600MPa to 800MPa resulting in SMC component densities typically in the range of 7.3 g/cm^3 to 7.5 g/cm^3.

III. Recent Development of Somaloy® 5P Materials

Höganäs AB have since the beginning of the 1990s developed and produced the Somaloy® SMC grades based on pure iron particles combined with inorganic coatings. The magnetic properties have been improved significantly since

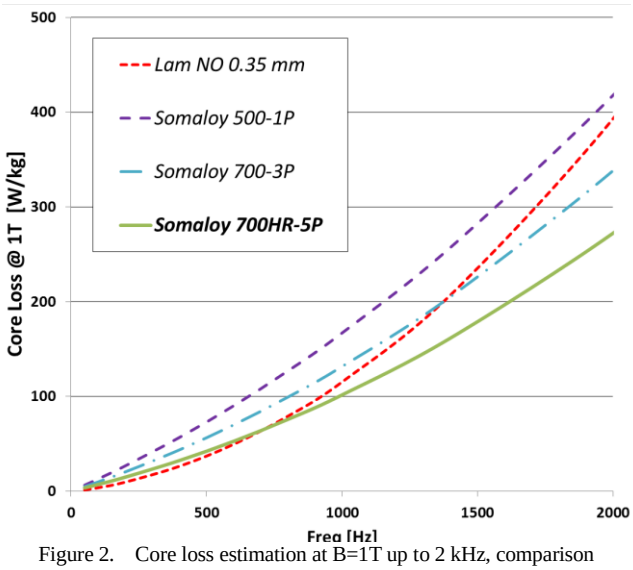


Figure 2. Core loss estimation at B=1T up to 2 kHz, comparison

the first introduction of Somaloy 500-1P in 1996, thanks to the focused development work done with the vision to supply state-of-art SMC products to the electromagnetic application market as shown in Table 1-3 and Fig.2.

The recently developed Somaloy® 5P technology [2] is based on a new inorganic particle coating that can be heat-treated at up to 650°C for optimal stress relief of the compacted particles. These high temperatures will drastically decrease hysteresis losses and thereby H_c from about 220 A/m for Somaloy 700-3P down to a level of 120 A/m for Somaloy 700HR-5P.

TABLE I. Overview of Somaloy® grades up to 2kHz

Material	Strength TRS [MPa]	Perm. µr_max [-]	Resistiv. ρ [µΩ m]	Induction B@10kA/m [T]
Somaloy 500-1P	50	500	70	1.51
Somaloy 700-3P	125	750	200	1.61
Somaloy 700HR-5P	**60**	**600**	**700**	**1.57**
Somaloy 1000-5P*	**60**	**850**	**70**	**1.63**

*application range <400 Hz

TABLE II. Overview of Somaloy® high frequency grades

Material	Strength TRS [MPa]	Perm. µr_max [-]	Resistiv. ρ [µΩ m]	Induction B@10kA/m [T]
Somaloy 130i-1P	30	290	8000	1.40
Somaloy 130i-5P	**45**	**330**	**>20000**	**1.46**

TABLE III. Typical loss Somaloy® high frequency grades

Material	Density P [kg/m^3]	Loss 1T/100Hz [W/kg]	Loss 0.1T/10kHz [W/kg]	Loss 0.1T/30kHz [W/kg]
Somaloy 130i-1P	7.35	12	27	110
Somaloy 130i-5P	**7.43**	**8**	**22**	**96**

The possibility to heat-treat the SMC component at high temperatures will also be mirrored in the maximum temperature of operation in the application. Somaloy components can quite easily stand constant temperatures up to about 200°C with no degrading over time. The particle coating will supply a basic resistance to corrosion similar to typical lamination steel sheets. In corrosive environment it is recommended to apply external corrosion protection.

Mechanical properties of SMC are different from laminated steel sheets. The strength is lower and the materials show a more brittle behavior that must be considered when handling the SMC components, performing secondary operations or assembling a structure. Machining of SMC components should be avoided due to the hard and brittle performances that may negatively influence the components properties. The best recommendation for assembly is to use gentle clamping and glueing.

IV. SMC Component Manufacturing and Design

SMC components of Somaloy® are formed and compacted into net-shape in a press with a specific tool set. The component design and how it will be pressed will set the specification of the press regarding complexity of tooling and maximum press force. The component design will have a direct impact on the component cost. Design-for-production aspects are recommended to be implemented as early as possible in the design phase.

The here described SMC materials are typically compacted at pressure levels of about 800 MPa or higher even up to levels of 2000 MPa in extreme cases. At these conditions the lubrication both internally in-between the particles and to the walls of the tool is very critical. Some lubrication systems like the Somaloy 3P will also require controlled temperature of the die to deliver optimal performance. The lubricant occupies some volume of the powder mix and high lubricant content will reduce the final density of the component.

It is popular to describe SMC materials as 3-dimensional but in fact there are two features covered in this designation. First is the almost isotropic material property that gives similar magnetization conditions in all directions. Secondly is the feature of 3-d forming of components that is connected to the production process. This means in practice that a SMC component with simple shape can utilize an advanced magnetic flux path. A too complicated 3-d shaped component may require quite complex and more costly tooling and press process.

When opening for 3-d flux path designs that are possible with the almost isotropic SMC materials will bring new design alternatives and new possibilities to optimize not only the magnetic core but also the winding.

A popular SMC feature is the 3-d ‘field concentration’ as shown in Fig. 3, which can allow adaption between a large permanent magnet area and a smaller cross-section area of the core in the coil. This feature combined with a more circular core shape can reduce the copper winding length significantly and the net result is decreased winding losses and also reduced winding cost. Flux concentration can open up for Ferrite magnets as a low-cost alternative.

Some machine topologies are designed for 3-d flux path’s and thereby specially aimed to utilize SMC components.

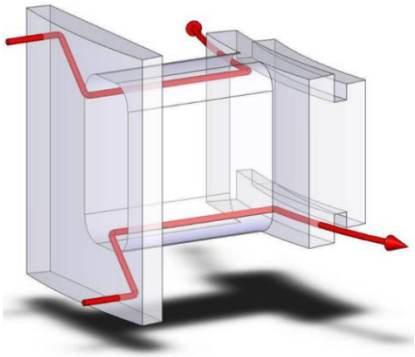


Figure 3. 3-dimensional flux concentration in SMC component..

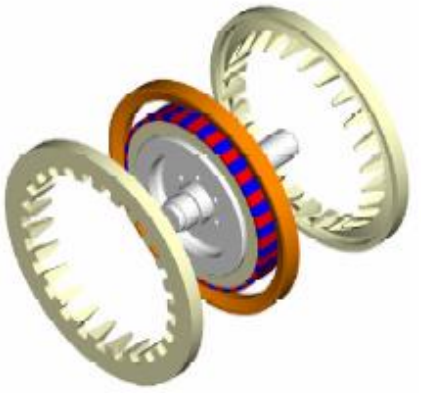


Figure 4. Clawpole TFM topology

Examples is the transverse flux machine (TFM) of clawpole type [3] shown in Figure 3 with modulated poles characterized by a single hoop winding and a large number of poles resulting in high torque densities.

V. SMC potential For magnetic bearings or bearingless applications

The unique combination of 3-dimensional resistance to high frequency eddy-currents can bring potential benefits using SMC compared to laminated steel-sheet cores; the low eddy-currents at higher frequencies can potentially increase bandwidth for a magnetic bearing system as described by Hijikata et al. [4]. Utilization of 3-d flux patterns can result in space efficient solutions like the combined radial and axial magnetic bearing described by Kim and Kim [5].

VI. Conclusions

Recent improvements of inorganic coating systems for Somaloy® 5P SMC materials have resulted in significantly reduced coercive force and hysteresis losses. Bulk resistivity remains at high level and the result is a non-alloy cost-efficient iron SMC material with losses competing <0.35 mm steel-sheet laminations.

For the application of these materials it is found important to consider both material and component forming processes early in the design work. It is also observed that a major part

of the component properties are set in the manufacturing process, at compaction and heat-treatment that also must be seriously considered in the component development. Further, some examples are identified showing potential improvement regarding bandwidth and compact, space efficient designs beneficially applicable for magnetic bearing systems.

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