

Advances in Soft Magnetic Composites – Materials and Applications

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ABSTRACT

Soft Magnetic Composite (SMC) challenges traditional material such as soft magnetic ferrites and electrical steels in applications with alternating magnetic fields. As the volume potential is large this is an interesting area for the P/M industry. By utilising the features offered by the material itself as well as the P/M forming technique new competitive electromagnetic designs can be realised. This paper will describe main features and benefits offered by the technology and emphasize suitable application area. Finally, the latest and future materials will be presented.

INTRODUCTION

SMC-materials (Soft magnetic composites) are basically iron powder particles separated with an electrically insulated layer as shown schematically in Figure 1. The powder metallurgy (P/M) process has for long time been used to manufacture SMC components for high frequency inductor applications. These traditional SMC materials consist generally of iron particles distributed in matrix of organic materials. Due to the distributed air gap and good high frequency behaviour cores made of iron based SMC materials is today still the most cost efficient solution for inductive components in various filter and power conversion applications.

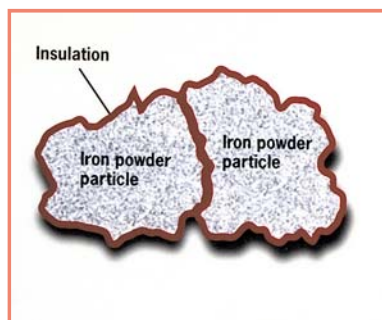


Figure. 1 Schematic picture of a SMC-material

Rather recently the group of SMC's has been expanded by the introduction of new materials. These materials do not contain any organic matrix that set limitations on the processing conditions. This makes it possible to manufacture components with significantly higher saturation induction, permeability as well as lower hysteresis losses. As a result SMC's are now also an alternative to electrical steels in applications in the low to medium frequency range such as rotating machines, sensors and fast switching solenoids. As

the technology still is rather young applications, material, process and application development is ongoing at a high pace.

Basically there are three main features offered by the technology.

1. Unique combination of magnetic saturation and low eddy current losses. Figure 2 positions the SMC compared to traditional materials.

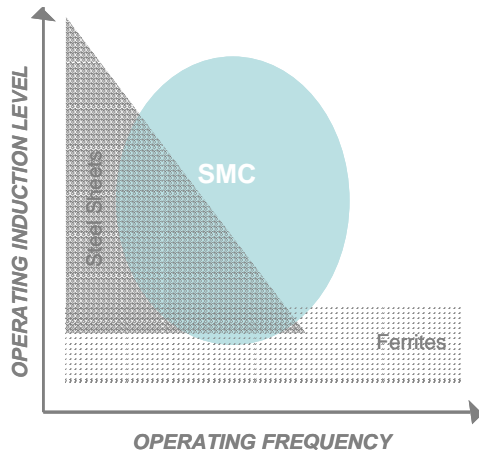


Figure 2: SMC, over bridges traditional materials

2. 3D-flux carrying capability. Figure 3 illustrates this feature in both simple geometry and in a more complex shaped part.

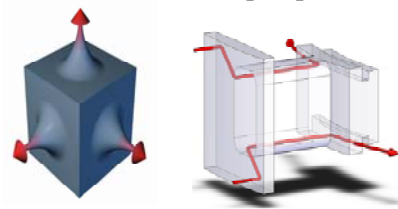


Figure 3: The 3D-flux capability illustrated in a simple and a more complex structure

3. Cost efficient production of 3D-net shaped component by the P/M process (figure 4).

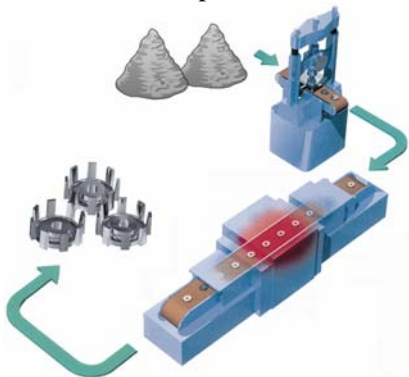


Figure 4: The powder metallurgy process

This paper will describe some of the benefits and trends with the technology as well as focus on the latest material development.

ELECTRICAL MOTORS

As the consumption of laminated steels for electrical motors is several times larger than the market for sintered structural parts this is an interesting target for the P/M industry. However, it is challenging as material, designs and manufacturing has been optimized for a 2D flux over a long period of time. A “drop-in” replacement of a laminated core by a SMC will result in best case in an equal performance at the same cost. One exception could be motors operating at high frequency where a direct replacement may result in some benefits. However, the key to success is found in utilising the three dimensional flux capability of the material. The possibilities for the designer to use new topologies with shape, winding and assembly solutions beyond today’s standards opens up for benefits such as better performance, reduced size and weight, fewer parts and lower cost.

A 3D design can be adopted for virtually all normal motor topologies. For instance a 3D-designed Universal motor can significantly reduce the Cu-wire and increase the performance of the application [1]. Despite of this it has proven difficult to commercialise SMC in both induction and universal motors. These motors operate at low net frequency which allows them to use thick low cost lamination. Furthermore, in these motors the reluctance in the magnetic circuit is low as the air gaps are small and there are no permanent magnets present. SMC has a lower permeability than laminations and this influences the magnetic flux in the circuit and needs to be compensated by adding more iron.

The trend toward high efficiency permanent magnet motors and features such as variable speed increases the competitiveness for the modern SMC materials. Motors can be designed to operate at higher frequencies as a controller is needed. The permanent magnet has a very large influence of the reluctance which limits the effect of the lower permeability of the SMC material. It has been shown that using SMC components in a redesigned state of the art radial flux BLDC motor for a high efficiency scroll compressor the performance can be matched [2]. In fact the performance could be matched by a motor taking up a significantly lower volume. In this example only the stator was redesigned leaving room for further improvements by optimising the control and rotor for a SMC design. Figure 5 shows the stator design used in this study.

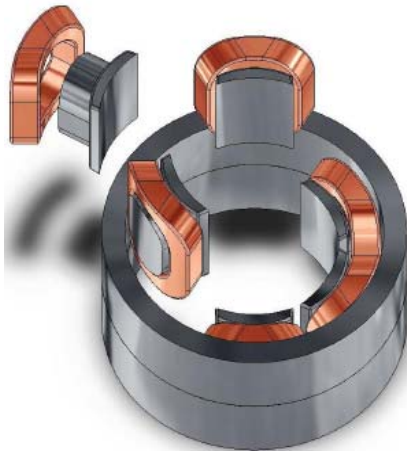


Figure 5: Re-designed Stator

Another very interesting motor topology for SMC is the axial flux motors. This has successfully been demonstrated in the life car project in UK where a high performance axial flux machine was designed for a traction application (Figure 6) [3]. In table 1 some of the motor characteristics are given.

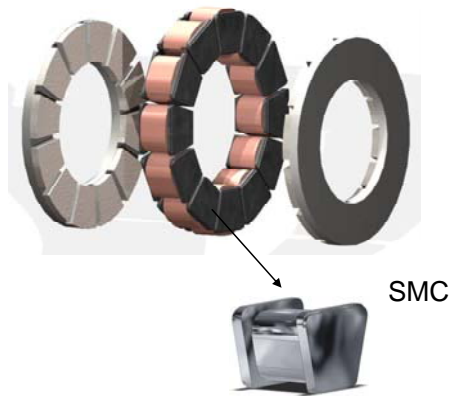


Figure 6: Axial flux motor designed and build by Oxford University

Table 1: Motor Performance

<i>Torque = 130Nm</i>	<i>Speed = 3600rpm</i>
<i>Power = 50kW</i>	<i>Frequency = 300Hz</i>
<i>Weight = 11kg</i>	

Perhaps are the most suitable motor topologies for SMC's Claw pole / TFM or linear machines. The Claw pole / TFM machines have a 3D flux path and are therefore difficult to manufacture with laminations. These machines normally have a very simple hoop winding which is attractive from manufacturing point of view. Figure 7 shows a claw pole topology studied by University of Newcastle [4] while figure 8 shows a simpler one phase topology studied by Lund University [5].

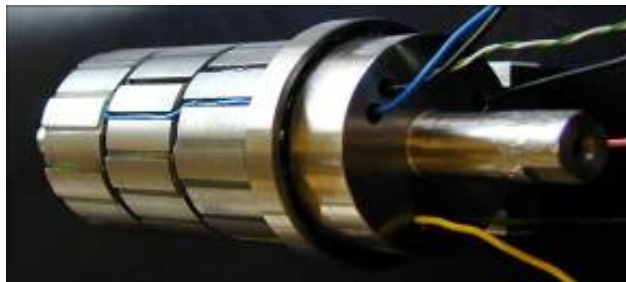


Figure 7: Three phase solution designed by University of Newcastle

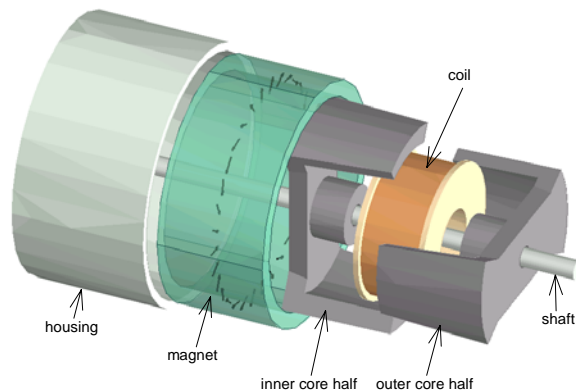


Figure 8: Single phase claw pole machine designed by Lund University

The most striking advantage by using SMC in linear machines is from manufacturing point of view. It is clearly illustrated in figure 9 that the number of parts can be decreased and assembly simplified by

changing from lamination to SMC. Moreover, by actually modifying the design for SMC the performance could not only be matched but improved [6].

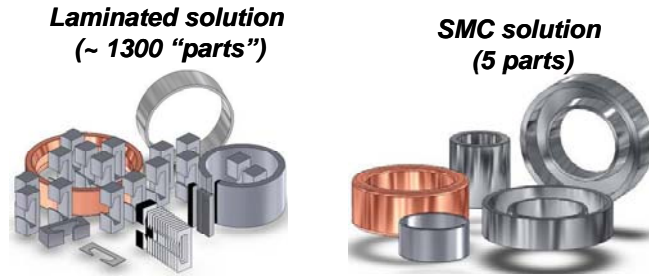


Figure 9: Parts required for laminated and SMC solution

MATERIAL DEVELOPMENT FOR ELECTRICAL MOTORS

As described in the previous section the competitiveness of the technology for motor applications depends to a large extent on the design. However, increasing SMC's material performance naturally increases the benefits of using the SMC technology. Over the last 10-15 years significant material improvements has been achieved and the development is still ongoing. Projects that were rejected in the past may now be realised due to the material improvements.

Compared to lamination SMC has higher DC-losses (but lower eddy-current losses) which needs to be considered in the design in many cases. Therefore, reducing the losses is important in order to increase the competitiveness of SMC in electrical motor.

Figure 10 shows the core losses/frequency as a function of frequency measure at 1T for a number of materials. Somaloy® is the brand name for the SMC materials from Höganäs AB. The traditional polymer bounded SMC material is represented by Somaloy 500+0,6% binder (LB1). Extrapolating the graphs to 0 Hz indicates the DC losses and the slop is an indication of the eddy-current losses. It can be seen that all material have a good response to the increased frequency as the slope is modest. It is also clear that even at 1000Hz the dominating loss is DC-loss.

More than 10 years ago the Somaloy 500 1P was introduced to the market which had close to 30 % lower DC losses compared to the polymer bonded materials. A few years ago the Somaloy 700 1P was released to the market which lowered the losses by another 10%. The latest material development led to another reduction of the DC losses, which corresponds to more than 60% reduction compared to the traditional polymer bounded SMC material.

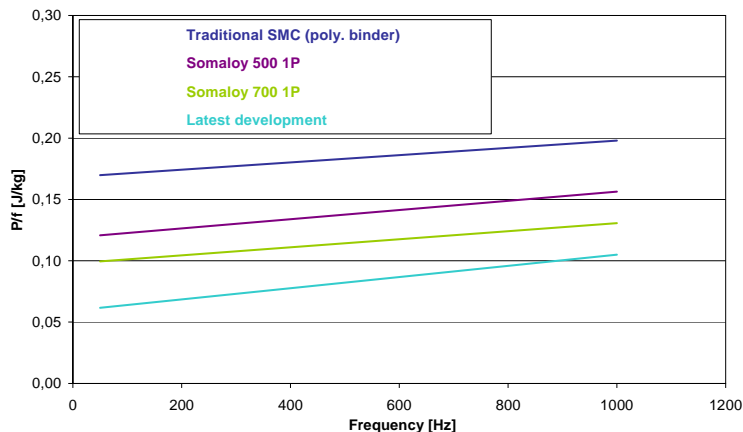


Figure 10: Losses/cycle (Core loss /frequency) plotted as function of frequency

The electrical resistivity of the SMC material gives an indication on the eddy current losses. In table 2 some SMC materials are compared to iron and alloyed sintered materials. It is clear that the electrical resistivity is several magnitudes greater than any alloyed material and this is the reason why SMC material and not sintered material is used in applications with alternating magnetic field. The improvement in resistivity from Somaloy 500 1P to Somaloy 700 1P makes the material more robust from a production point of view.

Table 2: Electrical resistivity of sintered and SMC materials

Material	Resistivity [$\mu\Omega\text{m}$]
Sintered iron	0,1
Sintered Fe+0,45%P	0,2
Sintered Ferritic Stainless	0,6
Somaloy 500 1P	70
Somaloy 700 1P	400

Losses are important for motor applications and the second important property is the B-H characteristics. Fortunately, the B-H characteristics have also improved which means that higher torque densities and/or lower Cu-losses can be obtained. Figure 11 shows the B-H curve for a selection of SMC materials.

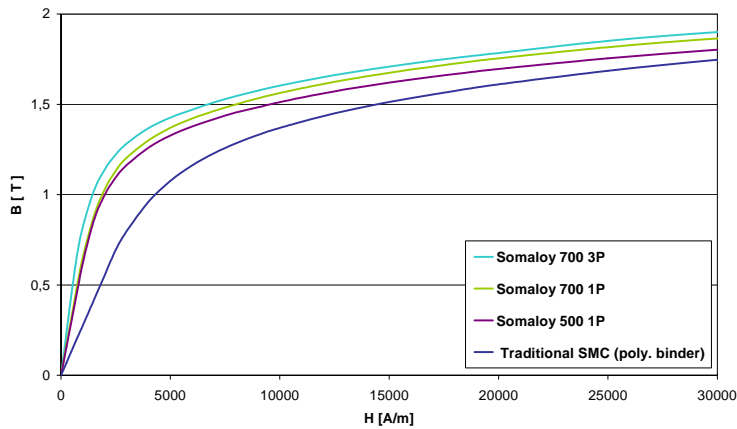


Figure 11: B-H curve

It is clear that significant improvement in B-H characteristics is obtained as compared to the polymer bounded material. One reason for the improvement of the B-H characteristics of the Somaloy 700 series is the extremely high compressibility of the powder. Figure 12 shows a compressibility curve for Somaloy 700 1P and compare it to ABC 100.30 which is also considered as a very compressible powder.

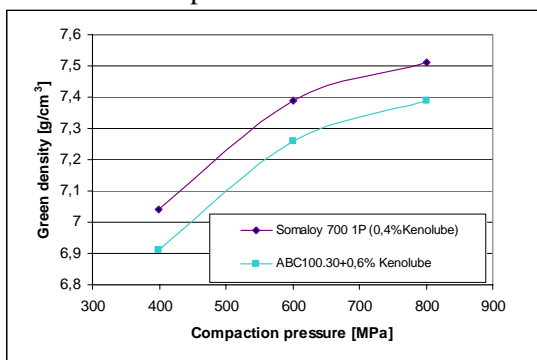


Figure 12: Compressibility curve of Somaloy 700 and ABC 100.30 (400MPa=28,8tsi; 600MPa=43,2tsi; 800MPa=57,6tsi)

Another very important property of SMC material is its mechanical strength. Since SMC materials is not sintered lower strength are typically achieved which needs to be considered in the design stage. Significant improvement was also achieved in this area. Materials that contain organic binders can be processed to relatively high strength as shown in table 3. However, these powders are quite often pressed without internal lubrication, which makes mass production much more challenging and costly. The Somaloy 700 3P material exhibits higher mechanical strength even if it contains internal lubrication. Another advantage with the 3P system is that its magnetic saturation and permeability are also improved compared to the other materials. Table 3 shows the mechanical strength at ambient temperature as well as at 150°C and the induction at 4000A/m for some selected materials.

Table 3: Transverse rupture strength and magnetic induction at 4kA/m

Material	TRS at 25°C [MPa]	TRS at 150°C [MPa]	Magnetic induction at 4kA/m [T]
SMC polymer bonded (Somaloy 500+LB1)	100	35	0,96
Somaloy 700 1P	40	40	1,31
Somaloy 700 3P	125	125	1,37

MATERIALS FOR ELECTRICAL MOTORS

Table 4 shows a selection of different materials suitable for electrical motor applications. Data on the latest material development are also included.

Table 4: Selection of materials suitable for electrical machines operating up to kHz range

Material	Resistivity [$\mu\Omega\text{m}$]	TRS [MPa]	B@ 10kA/m [T]	μ_{max}	Core loss @ 1T [W/kg]		
					100 Hz	400 Hz	1 kHz
Somaloy 700 1P	400	40	1,56	540	10	44	131
Somaloy 700 3P	200	125	1,61	750	10	46	137
Latest development	700	60	1,57	600	6	32	104

- Somaloy 700 1P: Very process friendly and is considered as the base line for PM machines operating at 50Hz to several hundred Hz.
- Somaloy 700 3P: This material offers a high mechanical strength and good B-H behaviour.
- Latest development: Offers very low losses which is important for high efficiency motors

FAST SWITCHING ACTUATORS AND PULSE TRANSFORMERS

SMC has been used for a long time as a core material for fast switching actuators in diesel fuel injectors for passenger cars. There is development ongoing and the technology is spreading to other fuel types and segments. Figure 13 shows an injector system that has been developed for CNG/LPG.



Figure 13: Fuel injector system for CNG/LPG gas developed by United D&A international Automotive Electronic Technology Co,Ltd

The SMC technology is very well suited for fast switching actuator applications as the response of the material is fast. Moreover the high magnetic saturation means that high force can be obtained. Compared to some competing technology both the material and process are cost efficient and there is also a possibility for make compact 3D-designs. SMC has the potential to breakthrough other applications in the field of fast switch actuators such as

- Vibration damping
- Magnetic bearings
- Electromagnetic valve actuation
- Electromagnetic suspension

The SMC technology has also been used for a considerable time in ignition systems as the core in the pulse transformer. This field of development is being pushed forward with tougher legislation on emissions. Placing new requirement on the older SMC materials but this also opens up possibilities in the competition with lamination.

It is central for both fast switching actuators and ignition systems to have SMC materials with good B-H characteristics and high saturation. Still today polymer bonded material is used in both actuator and ignition system and it is clear that new materials can offer increased performance. Figure 14 compares the B-H characteristics of three materials.

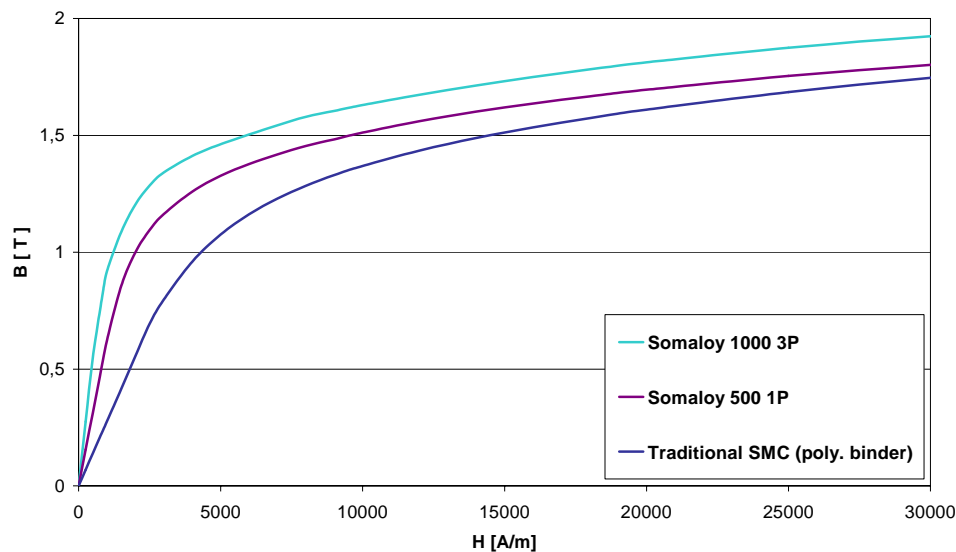


Figure 14: The B-H characteristics

Materials that is well suited for Fast switching actuators and pulse transformers can be found in table 5.

Table 5: Materials suitable for Fast switching actuators and pulse transformers

Material	Resistivity [$\mu\Omega\text{m}$]	TRS [MPa]	B@4kA/m [T]	B@10kA/m [T]	μ_{max}
Somaloy 500 1P	70	50	1,26	1,51	500
Somaloy 700 1P	400	40	1,31	1,56	540
Somaloy 700 3P	200	125	1,37	1,61	750
Somaloy 1000 3P	70	140	1,42	1,63	850

- Somaloy 500 1P: One of the most known SMC materials on the market and a base line for fast switching actuators.

- Somaloy 700 1P: Suitable for both fast switching actuator and ignition. A good material for geometries with high aspect ratios.
- Somaloy 700 3P: High magnetic performance and high strength makes this a very good material for fast switching actuators for fuel injectors but also for ignition cores with high demands
- Somaloy 1000 3P: Optimised for maximised B-H characteristics and strength

INDUCTORS FOR POWER ELECTRONICS

The use of power electronics is increasing in all kind of applications. The demand for high efficiency motor solutions and new application such as distributed energy generations requires converters and controls which also generates transient's and noise in electrical current. In order to protect equipment and not polluting the grid the market for various filters is increasing. Many of these filters uses inductors cores made of gaped steel sheet structures. Traditional SMC materials has for several decades been used in various inductor applications. Powder technology offers several advantages in these applications compared to steel sheets especially at the frequency ranging from kHz- to MHz. Two major benefits have been low eddy-current losses and the ability to store energy in the distributed air gap between particles instead of using a physical air gap, which can lead to problems due to the fringing flux. However, compared to steel sheets, SMC has suffered from lower saturation and also higher losses at low base and ripple frequencies. There is a trend towards higher frequencies, which increases the competitiveness of SMC materials, which offer lower eddy-current losses than laminates. Another factor is that the development of new SMC materials with higher saturation and lower losses in frequencies ranging from 1 to 50kHz makes it now possible to target application that uses gaped laminated inductor cores.

Switching from lamination to SMC new features can be used to create benefits. The 3D properties and 3D shaping can be used to make "new" compact geometries that for instance are common for soft ferrites such as the pot core (figure 15).

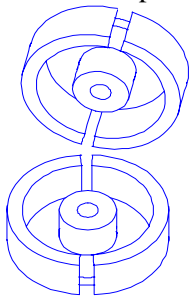


Figure 15: Pot core geometry

Rounded structure and smooth surfaces can be used to save Cu winding and to reduce the insulation which improves the thermal properties. Components can be made with close tolerances so modular or segmented structures can be used in order to optimise the production. The tool cost for powder pressing is in general lower than a stamping tool which means that it is easier to tailor the inductor for a specific application.

Often in filter applications there is a low base frequency with high amplitude and noise at higher frequencies and lower amplitudes. Figure 16 simulates the losses in this kind of operating conditions by simply adding losses measured at 1T and 50Hz and losses measured at 0,1T and 5 or 10 kHz.

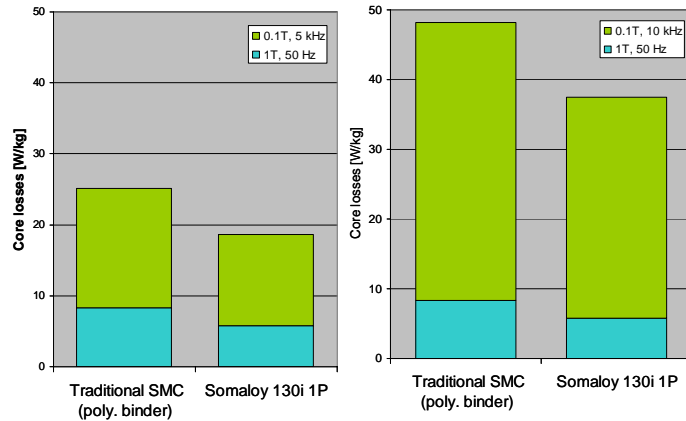


Figure 16: Losses at 1T&50Hz+0,1T&5 kHz and 1T&50Hz+0,1T&10 kHz

It is clear that under these operating conditions, the ripple current is the major contributor to the losses, especially at 10 kHz. It is also clear that the new SMC material has more than 20% lower losses compared to the traditional polymeric binder SMC material.

Table 6 shows two materials that could be used to replace gaped laminated components in power electronics applications.

Table 6: Materials suitable for inductive components in power electronics

Material	Resistivity [$\mu\Omega\text{m}$]	B@10kA/m [T]	Core loss [W/kg]		
			1T/100Hz	0,1T/ 10kHz	0,1T/30kHz
Somaloy 110i 1P	7600	1,33	15	26	85
Somaloy 130i 1P	8000	1,43	12	27	110

- Somaloy 110i 1P: the particle size is smaller than normal P/M grades because it is designed for higher frequencies maximum 100kHz.
- Somaloy 130i 1P: Is suitable for frequencies up to about 20kHz

PROTOTYPING

In order to evaluate a design, a prototype is generally needed. The straight forward method for prototyping is to produce blanks and then machine out the components needed. However, CNC machining of these new SMC materials that do not contain organic binder requires some experience and skills. It was also found that CNC machining can affect the B-H characteristics even though the part appears to be OK. This could lead to a large mismatch between the expected performance from simulation and the measured performance, which may result in the abandon of the project. There could also be issues with components that have been manufactured by EDM or electrode erosion. It has been found that materials with relatively low resistivity (e.g. Somaloy 500 1P, Somaloy 1000 3P) can be machined using these techniques without problem. However, for materials with higher resistivity, the erosion process affects the insulation negatively and the component ends up with much reduced resistivity. This can of course increase the eddy-currents losses and once again, lead to a large mismatch between simulations and measured performance, leading to project failure.

One solution for prototype components is to use a traditional polymer bonded SMC material and CNC machine the parts and then correlate the simulations with the prototype. However, as described earlier, the

difference in properties between the traditional SMC material and the newly developed are large, which may result in poor correlation.

A new material has been developed specifically for prototyping. The purpose of this prototyping material is to prove new design concepts by correlation simulations with measured data. The electromagnetic properties are good and quite close to Somaloy 700 1P and Somaloy 700 3P. CNC machinability has been improved significantly and properties are stable. However, EDM and Electrode erosion still affect the resistivity significantly which means that this method is not adequate if high resistivity is important for the desired part.

At the moment two geometries are available ($\varnothing 80 \times 20 \text{mm}$, $\varnothing 80 \times 40 \text{mm}$) in the prototyping material. Table 7 compares some material properties measured on rings samples that was CNC machined from these blanks with pressed samples made of Somaloy 700 1P. The magnetic properties of the prototyping material is close to the Somaloy 700 1P material

Table 7: Comparison prototype material and Somaloy 700 1P

Material	Resistivity [$\mu\Omega\text{m}$]	TRS [MPa]	B@ 10kA/m [T]	μ_{max}	Core loss @ 1T		
					50Hz	400Hz	1000Hz
Somaloy prototyping material $\varnothing 80 \times 20 \text{mm}$	280	80	1,53	455	5	46	138
Somaloy prototyping material $\varnothing 80 \times 40 \text{mm}$	280	75	1,46	430	5	48	147
Somaloy 700 1P	400	40	1,56	540	5	44	131

Figure 17 shows a claw pole structures that is being machined of a blank made of the Somaloy prototyping material.



Figure 18: Claw pole structure being machined from Somaloy prototyping material.

Larger structures than $\varnothing 80 \text{ mm}$ parts has successfully been made by machining segments that has been glued together in order to form a larger body that can be machined to the final shape (see figure 18).



Figure 18: Larger structures made by machining and gluing segments together.

However, making the prototype components by pressing the components in a tool instead of using machined parts has significant advantages.

- Cost efficient if many components are required
- The design is assessed from a production point of view
- True component properties are achieved
 - o Electromagnetic
 - o Mechanical
 - o Surface
- Tolerances are established
- Fast and accurate to evaluate different materials

SUMMARY

The material development of SMC materials has led to materials with increased performance such as lower losses, higher permeability and increased mechanical strength. These improvements increase the competitiveness of technology and the development continues. The latest development shows that even lower losses can be expected in the future.

For successful implementation of SMC in electrical machines 3D-designs are very important. Examples of motor topologies that suite the technology is TFM/Claw pole, axial flux and linear machines.

The combination of high magnetic saturation, fast response and cost efficient production of compact 3D shapes makes the SMC technology very attractive for fast switching actuator applications.

Inductive components made of lamination and that today require a gaped structure can be challenged by the new SMC materials.

A new SMC prototyping material has been developed in order to quicker and with greater accuracy correlate simulated performance with measured result on a prototype.

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