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A new generation of sustainable SMC materials with low core loss

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Abstract

Electrification pushes the agenda of soft magnetic material development, with increased demands on efficient low loss materials with minimal environmental impact. Soft Magnetic Composites (SMC) challenges traditional magnetic materials such as soft ferrites and electrical steels in applications with alternating magnetic fields, and can many times offer a solution that is more efficient and with lower carbon footprint. In comparison to those traditional materials, however, the relatively higher hysteresis has so far limited wide application of SMC. This paper presents a new material which combines an improved base powder and a newly developed water-based coating, into a product with lower hysteresis losses than any previous SMC material, combined with improvements in processing and application.

This paper introduces Somaloy® 7P, discusses the effect of manufacturing process parameters, such as compaction, heat treatment atmosphere, on component performance. Furthermore, the effects of operating temperature on component properties are investigated.

Keywords: SMC, electrification, sustainability

Introduction

Soft magnetic composite (SMC) materials are soft magnetic powder particles that are separated by an electrically insulating coating layer, that inhibits eddy currents to move between particles in the pressed component. SMC can be used in a wide range of applications, from relatively low frequency applications such as electric motors, to high frequency applications such as passive components for power electronics1,2). Depending on the application, the SMC material can be tailored by choosing the appropriate powder particle size, coating thickness, and processing conditions1-5).

For motor applications it is important with high permeability, induction and mechanical strength, and especially low magnetic core losses which are directly related to the system efficiency. The core losses can be divided into hysteresis losses, intra-particle eddy current losses, and inter-particle bulk eddy current losses. SMC materials have, compared with electrical steel sheets, the benefit of each particle being insulated which minimizes the bulk eddy current losses3). On the other hand, the hysteresis losses are higher, and this has been a main hinder for wide application of SMC materials. The higher hysteresis losses in SMC materials are due to "imperfections" in the material, such as grain boundaries, residual stresses from compaction, and the air gap between the particles. An important step towards minimizing the hysteresis losses was taken with the Somaloy® 5P coating, which enables heat treatment at 650 °C yielding full stress relaxation in the component4-5).

In this work we have successfully developed a new SMC material called Somaloy® 7P, based on an improved iron powder and a new multi-layer coating concept, for further reduction of hysteresis losses. The new coating concept is unique in being water-based, addressing the increasing focus on sustainability in electrification. This paper compares the new material to currently available materials and investigates the effects of processing conditions and application temperature in terms of thermal aging.

Experiment

Somaloy® 700 7P is the first product with the new 7P coating concept to be industrialized and is currently undergoing qualification. Some results in this paper are from earlier stages in the development, thus the absolute values may differ somewhat between different sections. All base powders used were water atomized, with average particle size of around 100 microns. The SMC powders were compacted at 800MPa into OD55/ID45/H5 mm magnetic square toroids, at 100 °C die temperature if not stated otherwise. Heat treatment of compacted parts was done in a furnace with nitrogen atmosphere and a controlled amount of air (0-20000 ppm O_2), with a top temperature of around 640 °C.

Electrical resistivity was measured using a 4-point probe method with 20 mm distance between measuring points.

For the measurement of magnetic properties, the toroids were wound with 100 drive and 100 sense turns of resin coated copper wire (diameter 0.63 mm) and measured using a Brockhaus MPG 200D.

Transverse rupture strength (TRS) was measured according to SS-EN ISO 3325:2000, on bars with dimensions of 30x12x6 mm.

Results and Discussion

A. Performance of the new material

Somaloy® 7P materials are press-ready mixes including an internal lubricant system, that can be said to be part of the coating system. The 7P coating concept is unique in being water-based, but it shares many chemical similarities with the 5P coating concept, thus the recommended die temperature is in the same range, 60-100 °C, depending on compaction pressure, particle size and part geometry.

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Heat treatment temperature profile is similar, with lubricant burn-off up to 450 °C, followed by coating activation, and finally stress relief at typically 640 °C (650 °C for 5P). Importantly, and different compared to previous materials, the heat treatment of Somaloy® 7P requires a controlled amount of oxygen, typically 10000-20000 ppm, in the atmosphere to achieve the desired resistivity.

Table 1 shows a performance comparison between Somaloy® 700 7P (100 mesh) and a selection of currently available SMC materials for motor applications. It is evident that the 5P coating concept achieved a major improvement in coercivity and losses compared to previous materials (1P and 3P), and that 7P takes this one step further. Comparing the 100 mesh versions of 7P and 5P, 7P is based on an iron powder with higher purity, less fine particles, and smoother surface morphology, which leads to a reduced coercivity. The improved base powder in combination with the 7P coating concept enables a thinner coating to achieve the desired resistivity. This minimizes the air gap between particles and increases the permeability and induction, which is evident also from the B-H-curve shown in Fig. 2. All together this contributes to the reduction in core losses, which are presented at 1T at various frequencies in Fig. 3. At very low frequencies, where the hysteresis losses are dominating, the reduction is close to 20% and a level similar to 700HR 5P. At higher frequencies the benefits of 130i 5P in keeping the eddy currents to a minimal is maintained, through the high resistivity and relatively smaller particle size compared to 700HR 5P.

Table 1. Selection of materials for motor applications.

Material	Resistivity (μΩ×m)	TRS (MPa)	B @ 10kA/m (T)	Hc (A/m)	μmax	Core losses @ 1T (W/kg)		
						100 Hz	400 Hz	1000 Hz
Somaloy® 700HR 1P	1000	35	1,53	210	440	10,0	43	125
Somaloy® 700HR 3P	600	120	1,57	217	770	10,0	45	130
Somaloy® 700HR 5P	700	60	1,57	120	600	6,6	30	92
Somaloy® 130i 5P	>10000	35	1,47	165	350	8,0	32	93
Somaloy® 700 7P	>10000	60	1,58	140	500	6,5	29	83

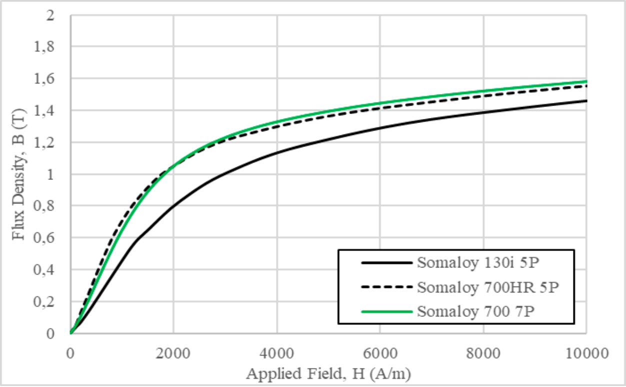

Fig. 1. Magnetic flux density as a function of applied field.

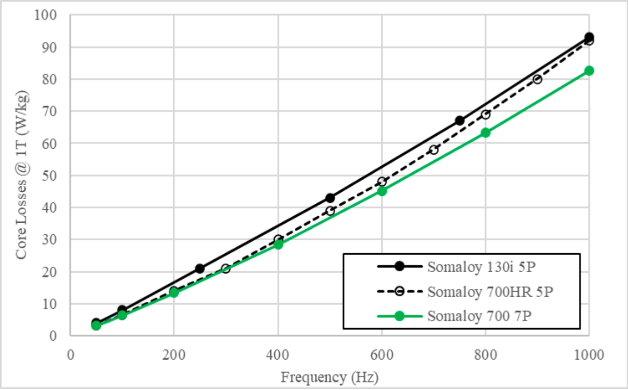

Fig. 2. Core losses as a function of frequency.

B. Effect of oxygen content in the heat treatment atmosphere

In order to gain all the benefits of the 7P coating concept, it is very important to have a controlled amount of oxygen in the heat treatment atmosphere. Table 2 shows the properties of samples that were heat treated at a maximum temperature of 640 °C, with varying oxygen concentration in the atmosphere. Resistivity increases with the oxygen concentration, however above 20000 ppm the coercivity increases and thus also the hysteresis losses. The optimum oxygen concentration and temperature profile should be tailored depending on the furnace, the geometry of the part, and the desired properties for the application.

Table 2. Effect of oxygen content in the heat treatment atmosphere on the performance of Somaloy® 7P.

[O2] in HT-atmosphere (ppm)	[O] (wt%)	TRS (MPa)	Resistivity (μΩ×m)	Hc (A/m)	Core losses @ 1T,1kHz (W/kg)
1000	0,14	60	200	142	78,9
3000	0,15	58	1100	142	77,3
5000	0,16	57	1400	144	77,4
10000	0,16	59	2900	143	77,1
20000	0,14	60	4700	142	77,1
50000	0,18	67	9800	147	78,7

Apart from the improved magnetic performance of Somaloy® 7P compared with 5P, another important improvement is the mechanical strength. Comparing with the 100-mesh 5P material, 7P increases the TRS from 35 MPa to 60 MPa, as shown in Table 1. Furthermore, the 7P concept opens up for further increase in TRS by tailored heat treatments, as shown in Table 3. By adding a pre-oxidation step before the heat treatment, for example at 250 °C for 2 hours in air, the TRS can be increased to more than 90 MPa, without damaging other properties. Is it likely that the pre-oxidation helps the lubricant to burn off in a beneficial way. Table 3 also shows that during the de-lubrication, it is beneficial to avoid oxygen in the furnace atmosphere, otherwise the coercivity increases due to oxidation of the iron powder. TRS values of up to 100 MPa have been achieved, demonstrating the possibilities to tailor the processing to optimize different properties.

Table 3. Mechanical and magnetic performance as a function of the heat treatment conditions.

Sample	Pre-ox.	Heat treatment	TRS (MPa)	Resistivity (μΩ×m)	Hc (A/m)	Core losses @ 1T (W/kg)	
						400 Hz	1000 Hz
1	No	HT 1 (Ref)	67	17000	136,3	28,2	82,7
2	No	HT 2	90	3200	140,0	28,9	85,2
3	No	HT 3	100	6800	144,0	29,3	85,7
4	250C, 2h air	HT 2	92	11200	139,4	28,6	84,0
5	250C, 2h air	HT 3	100	13900	147,0	29,8	87,2
6	250C, 2h air	HT 4	82	11000	134,5	27,8	82,0
HT 1	Reference heat treatment. All in 1% O2						
HT 2	Longer de-lubrication in 0% O2. Relaxation higher temp and shorter time, in 0,5% O2.						
HT 3	Same as HT2 except 1% O2 in De-lube						
HT 4	Same as HT2 except relaxation at lower temp and longer time.						

C. Effect of die temperature

As with other SMC materials, die temperature is an important parameter that affects the properties significantly. For Somaloy® 7P, warm die compaction is recommended. Table 4 shows that both mechanical strength and magnetic properties are improved compared to non-heated die, due to the positive effects of increased density. Density could be increased further by using die wall lubrication, see section D.

Table 4. Effects of die temperature on mechanical and magnetic properties.

Die temp. (°C)	Density (g/cm^3)	Resistivity (μΩ×m)	GS (MPa)	TRS (MPa)	B @ 10kA/m (T)	Hc (A/m)	μmax	Core losses @ 1T (W/kg)		
								100 Hz	400 Hz	1000 Hz
100	7,50	12800	13	65	1,59	141,4	522	6,5	28,7	82,9
RT	7,42	19500	8	55	1,53	141,1	424	6,8	29,8	87,0

D. Die wall lubrication for increased density and lower losses

There is an increasing interest in industry to use die wall lubrication to reduce the amount of internal lubricant, and reach higher densities and thus higher induction, permeability, and lower hysteresis losses. However, many coating concepts in the market do not work well with die wall lubrication, as the resistivity is ruined in the process. Table 5 shows that die wall lubrication is a very viable option for Somaloy® 7P. There is a slight drop in resistivity and TRS, which could potentially be increased with an optimized heat treatment. On the other hand, density is significantly increased, together with an increased induction and lower hysteresis losses.

Table 5. Magnetic performance at different lubricant content.

Lubricant content	Other	Density (g/cm^3)	Resistivity (μΩ×m)	TRS (MPa)	B @ 10kA/m (T)	Hc (A/m)	Core losses @ 1T (W/kg)		
							100 Hz	400 Hz	1000 Hz
0,1%	DWL*	7,63	12100	57	1,64	139,8	6,1	27,0	78,3
0,3%		7,50	12800	65	1,59	141,4	6,5	28,7	82,9
0,4%		7,46	14300	73	1,56	142,6	6,7	29,3	84,6
**DWL sample compacted at 1200 MPa @ 60 °C die temperature*									

E. Thermal aging properties

The thermal environment for the soft magnetic material can vary significantly depending on the application. It has been shown before that the core losses for SMC materials decrease with the operating temperature, due to the resistivity of pure iron increasing with temperature$^{1)}$. Another aspect of the operating temperature is how it affects the material properties over time, so called thermal ageing. A study was performed where different materials were exposed to temperatures between 150 °C and 260 °C for 120 hours, followed by magnetic testing at room temperature. The values were then compared with the values obtained before the temperature exposure. Table 6 summarises the results, which show that 7P is much less affected by thermal aging compared to 5P, with viable top temperatures increasing from around 150 °C to around 250 °C. This indicates an improvement in how well the coating covers the whole powder particles, which is also supported by the fact that 700 7P has similar resistivity to 130i 5P although the coating thickness is more similar to the thinner one of 700HR 5P.

Table 6. Thermal aging effects on core losses.

	Core Loss increase @1T,1kHz after 120h		
Material	150 °C	200 °C	260 °C
Somaloy® 700HR 5P	5%	10%	-
Somaloy® 130i 5P	6%	-	40%
Somaloy® 700 7P	0%	1%	5%

Conclusion

A new generation of soft magnetic composite materials has been presented, based on an improved base powder and an innovative water-based coating process. The new material has benefits compared to the state-of-the-art SMC materials for motor applications, with lower core losses across the whole range from 0-5 kHz. The mechanical strength is improved, with almost double the TRS value compared to the corresponding 100-mesh Somaloy® 5P-material (130i).

The processing of the powder is very similar to Somaloy® 5P but has even more possibilities of tailoring the properties for the application. By optimizing the heat treatment conditions, the mechanical strength can be increased a further 40-50%. By using die wall lubrication, which is a very viable option for the new material unlike many other SMC materials, the density can be maximised to minimize the core losses.

In the application, it has been demonstrated that the new material is less affected by thermal aging than previous materials, increasing the viable top operating temperatures to up to 250 °C.

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