The Effect of Manufacturing Processes on the Properties of Multi-layer Coated SMC Components

Zhou Ye, Björn Skårman
Höganäs AB, Höganäs, S-26383 Sweden

ABSTRACT

Multi-layer coated pure Fe-based soft magnetic material is a recently developed new generation of Soft Magnetic Composite (SMC) which has low hysteresis core loss due to its thermally stable, high temperature electrical insulation coating. These SMC materials can preferably be used for various electrical machines and other inductive components designed for higher operating frequencies up to several kilo Hz. Both magnetic properties and other performance of a SMC component depends not only on the powder material itself, but also on the component manufacturing processes. This paper investigate the effect of the manufacturing processes, including compaction pressure, die temperature, heat treatment temperature, heat treatment time as well as heat treatment atmosphere, on the final properties of the SMC component. Finally, a proposal of an optimised process recommendation for the manufacturing of Somaloy ®5P components is made.

Introduction

The most of SMC-materials are pure iron powder with an electrically insulated coating. Cores made of SMC materials can be used for electric drive systems and other inductive components designed for higher operating frequency applications[1-3]. Insulated coating is one of the key factors to balance of good permeability, low core loss and good mechanical strength, which are very important properties for SMC applications. A multi-layer coated SMC, as called Somaloy 5P, has been developed by Höganäs AB [4]. This new developed coating concept enables heat treatment at 650°C, providing complete stress relief so that SMC materials with this insulting layer have 30-45% lower hysteresis loss than earlier SMC materials. On the other hand, the electromagnetic and mechanical properties of the finished component will depend not only on the SMC- powder but also on the mix, i.e. the added lubricant, and component manufacturing processes, including compaction and heat treatment. A low amount of additive or high compaction pressure results to higher densities, which is beneficial for the magnetic properties. During compaction, stress is introduced in the particles, which deteriorates the soft magnetic properties. The higher the heat-treatment temperature is set, the higher the degree of stress relief. The highest recommended heat-treatment temperature for Somaloy 5P powders is 650°C. For this multi-layer coated SMC, it is important not only to control max heat treatment temperature, but also to optimise heating process from rooms temperature to desired max temperature. The main aim of this paper is therefore to, in more detail, present the influence of compaction and heat treatment parameters on the SMC-material property profile. Finally, a proposal of an optimised process recommendation for the manufacturing of Somaloy ®5P components is made.

Experimental details

SMC material used for this investigation was Somaloy 700 HR 5P. Its mean particle size is about 250µm. Magnetic toroids with an inner diameter of 45 mm, an outer diameter of 55 mm, and a height of 5 mm were samples for magnetic properties evaluation. Toroid samples have 100 drive and 100 sense turns winding. The core loss and B-H curves were measured using a Brockhaus hysterisisgraph 200. Transverse Rupture Strength (TRS) was measured according to ISO 3995. The specific electrical resistivity was measured on the ring samples by a four point measuring method.

Results and discussion

1 Compaction

1.1 The effect of lubricant content and compaction pressure

SMC-materials take direct advantage from the well-established compaction technology for traditional Powder Metallurgy -materials. The most important compaction parameter influencing material performance is the compaction pressure. It is always beneficial to compact at as high compaction pressure as possible. Higher density means higher induction for a certain applied field, leading to benefits such as higher torque in rotating machine applications. On the other hand, compacted component density is always related to the lubricant content. Somaloy 700 HR 5P is a press-ready mix. Its minimum lubricant is 0,3 wt% and then amount of lubricant can be increased if it is necessary depending on components geometry. Figure 1 shows the effect of compaction pressure on the component density of 3 mixtures with 0,3, 0,4 and 0,5wt% lubricant content. Here components are compacted at 800MPa with a die temperature of 100ºC. In general, this material has a good compressibility. As normal PM powder, higher compaction pressure and lower lubricant content give high density. High compaction pressure gives more effect for the mixture with low lubricant amount. The effects of compaction pressure and lubricant content on the component magnetic performance are shown in table 1. The toroid samples is heat treated at 650ºC and N2 atmosphere. High lubricant content gives high resistivity which is important for high frequency or large cross section component applications [5]. The lubricant has not only a function for decreasing ejection force, but also a function for protection of insulation coating during the compaction. However high lubricant content will decrease maximum permeability (µmax) somehow. The compaction pressure effect on the permeability is more complicated. A combination with low lubricant content, a high pressure increases permeability, but combination of high lubricant content and high compaction pressure leads a lower permaebility. Low lubricant content and high compaction pressure lead a low core loss.

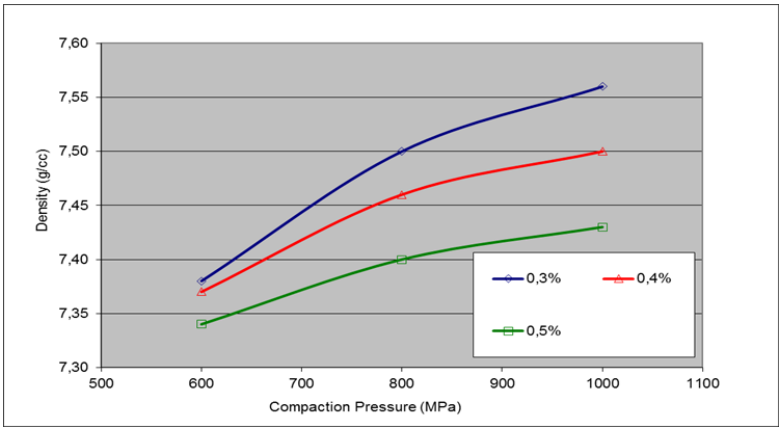


Figure 1 Effect of the compaction pressure on the component density

Table 1 The effect of compaction pressure and lubricant content on the component performance

Lubricant content (wt%)	Compaction pressure (MPa)	Resistivity (µΩ.m)	µmax	Loss@1T400Hz (w/kg)
0,3	600	350	560	37,6
	800	600	580	33,8
	1000	620	600	32,8
0,4	600	520	556	38,2
	800	900	580	35,0
	1000	1000	570	34,6
0,5	600	560	580	38,0
	800	1200	560	35,9
	1000	1400	520	35,8

1.2 The effect of die temperature

The Somaloy 5P materials behave similar as the Somaloy 1P materials [6] as the temperature of the die can be either cold or heated. However, the magnetic and mechanical performance will be dramatically improved if the die can be controlled at a moderate temperature. “Controlled die temperature compaction” (i.e. a moderate increase in tooling temperature) will also improve the lubrication, leading to improved ejection behaviour as well as increased density. It is important to notice that for “controlled die temperature compaction” only the tool die (and optionally punches) are heated up and not the powder mix. The optimum tooling temperature will depend on factors such as part geometry, compaction pressure, choice of tooling materials, potential coating of the tooling, etc. Generally, all properties except for the electrical resistivity will be improved when the temperature of the ejected part increases up to about 100°C. In other words, the die temperature may be used as a tool to control the resistivity of the final heat treated component. The importance of die temperature on the BH curve is shown in Figure 2 and the effect on other properties is shown in table 2

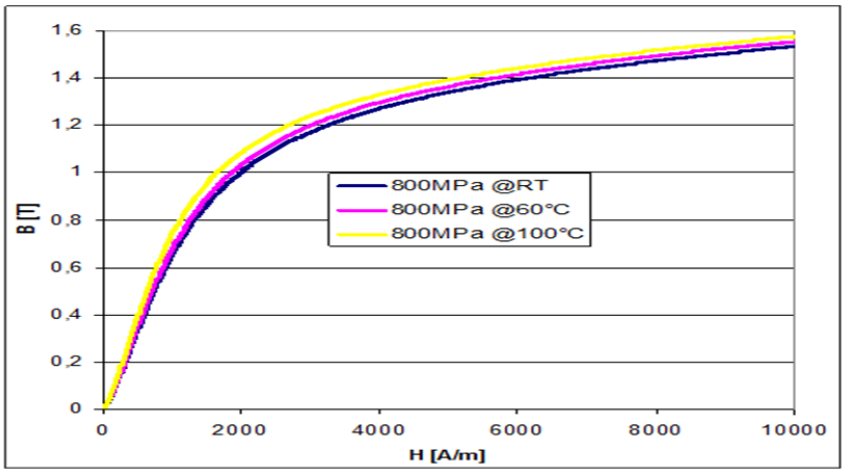


Figure 2 BH-curves of Somaloy 700HR 5P (0.3wt% 5P Lube)

Table 2 The effect of die temperature on the component performance

Die temperature (ºC)	Density (g/cm^3)	TRS (MPa)	Resistivity (µΩ.m)	µmax	Loss@1T400Hz (w/kg)
RT	7,44	50	1800	480	36,0
60	7,48	56	900	560	33,8
100	7,50	60	620	600	32,8

2. Heat treatment

A unique property of SMC-materials is their high resistivity (in three dimensions). The resistivity of a component depends on the properties of the electrically insulation coating on each particle. The coating will start to deteriorate at higher temperature due to thermally activated diffusion processes, leading to decreased component resistivity.

The heat treatment operation is performed in order to release the lubricants from the component, obtain partial or complete stress relief of the component after compaction and, finally, to gain additional strength[7]. In practice, the temperature selected should be the highest possible to ensure high stress relief but without destroying the electrically insulating surface coating. Somaloy 5P coating is a multi-layer coated SMC. Except for de-waxing and stress relieving, it is very important to let the coating ingredients to react both in a particle and between particles at a moderate temperature in order to gain strength and good resistivity.

2.1 The effect of maximum heat treatment temperature

Fig. 3 shows the effect of heat treatment temperature on the coercivity of Somaloy 700HR 5P. As heat treatment temperature rises from 550ºC to 650ºC, the coercivity decreases from 190 A/m to 115 A/m. However, a further increase of temperature above 650°C will not reduce the coercivity anymore because the stress in plan-Fe particle from compaction reliefs completely at 650ºC. On the other hand, the coating will start to deteriorate at higher temperatures due to thermally activated diffusion processes, leading to decreasing component resistivity as shown in the same figure. This shows a direct effect on the core loss. Here rinsing temperature from 550ºC to 650ºC, hysteresis(DC) loss decreases gradually and eddy current loss keeps almost at the same level. However rinsing temperature further from 650ºC to 750ºC, hysteresis(DC) loss does not change so much, but eddy current loss increases rapidly due to rapid resistivity decreasing.

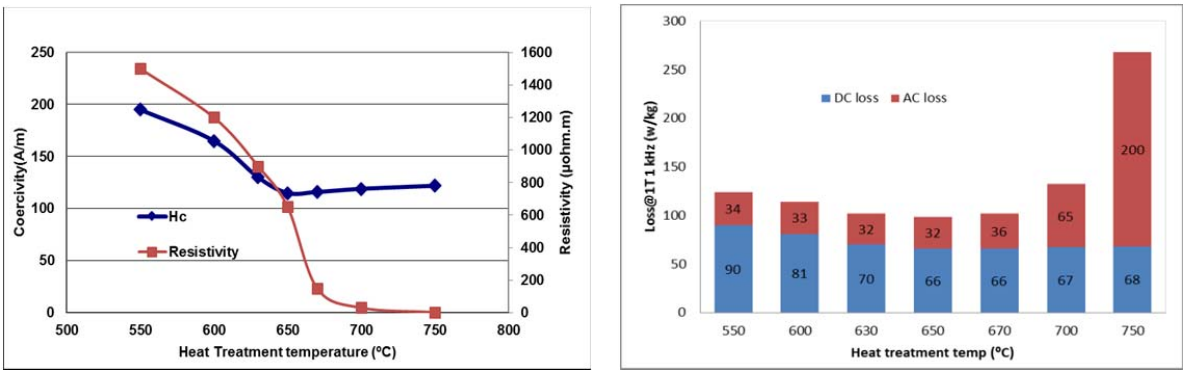


Figure 3 The effect of heat treatment temperature on the coercivity, resistivity and core loss

2.2 Single or double steps heat treatment

Two different heat treatments have been tested. One is direct heating from room temperature to 650ºC at a heating rate about 15ºC/minute and then to keep the component at 650ºC for 15 minutes. Another is to heat component to 450ºC at a heating rate about 15^{0}C/minute, to keep it at this temperature for about 15 minutes, to continually heat the component to 650^{0}C at about 10-15^{0}C/minute and then to keep the component at 650^{0}C for 10-15 minutes. Both processes are schematically shown in figure 4. It is obvious that heat treatment with two steps gives a better performance. Of course, a direct heating process works also and it will save the processing time. A possible compromise of these two processes is a one-step process with slow heating rate.

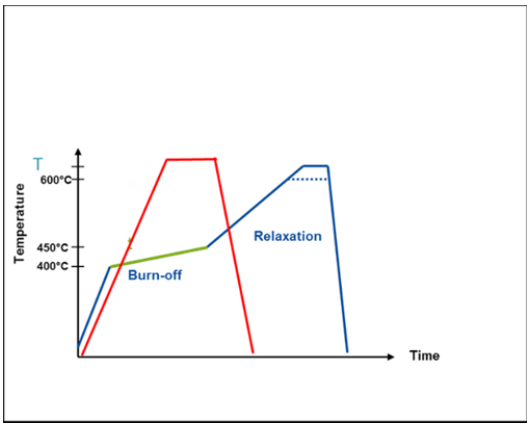


Fig. 4 Two different heat treatment processes

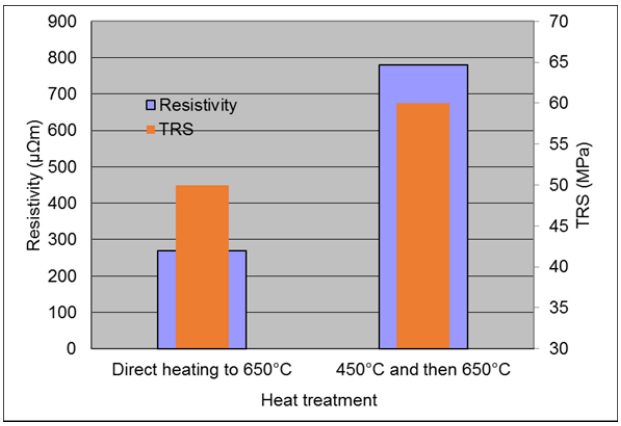


Fig. 5 Some component properties with these process

2.3 The effect of oxygen content in nitrogen

The atmosphere during heat treatment is another of important process parameters. For the most SMC material, a no-reductive atmosphere is preferred because most insulation coatings are some type of oxide. However a good insulation coating layer is very thin, which is hard to protect base pure metallic powder from oxidation. A serious oxidation of powder will lead to worsen magnetic properties, such as poor resistivity and high coercivity. Especially for Somaloy 5P material, the maximum heat treatment temperature is high up to 650ºC. At such high temperature, components will be more sensitive to the oxygen content. In this study, components with different densities from 6,8 to 7,5g/cm3 have been heat-treated in an atmosphere from pure nitrogen (0% oxygen) to 100% air (21% oxygen), by mixing a different amount of nitrogen and air. The effect of oxygen content in nitrogen on core loss at 1T and 1kHz of Somaloy 700 HR 5P components are shown in figure 6. The sensitivity of Somaloy 700 HR 5P to oxygen content in heat treatment atmosphere is strongly related to component density. For a component with 7,5g/cm^3 density, it can be treated in an air atmosphere and keeps as good performance as in pure nitrogen. However, for a component with only 6,8/cm^3 density, it should be heat-treated in pure nitrogen atmosphere to avoid poor performance. The results are very logical because a component with low density has many open and large pores which will lead to oxygen deeply penetration inside the component. The oxidation will take place in the whole part. In opposite way, a component with high density has less open pores and pores are small, which will makes oxygen difficult to penetrate in inside the component. The oxidation on surface could close to pores and then protect the inside oxidation.

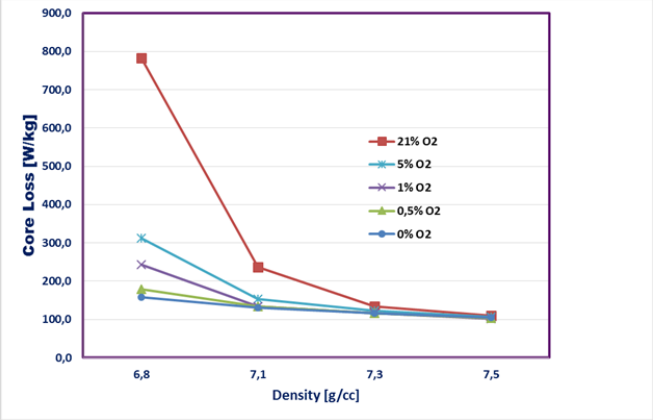


Figure 6 The effect of oxygen content in nitrogen on core loss

Conclusion

A SMC component made of multi-layer coated Somaloy 700HR 5P can be processed similarly as other Somaloy products. Suitable amount of lubricant content, higher compaction pressure and warm die will give both better magnetic and mechanical performance. A two steps heat treatment will give both high strength and high resistivity. A higher density component of Somaloy 700HR 5P is less sensitive to the oxygen content in heat treatment atmosphere. It is recommended that the component of this SMC material should be compacted at a pressure of 800MPa or higher with heated die at about 100ºC, and the compacted component should be heat-treated by two steps (at 450ºC for dewaxing and activating coating, and 650ºC for stress relieving) in an atmosphere of pure nitrogen or nitrogen with low amount of oxygen.

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