Novel Iron-Based FeSi Mixes for Inductor Applications

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ABSTRACT:

This study presents a novel soft magnetic composite powder that is suitable for the preparation of soft magnetic components working at high frequencies, such as inductors or reactors for power electronics. The material is a combination of Somaloy 110i 5P, a pure iron powder with a coating capable of withstanding heat treatments at 650°C or higher, and a low loss gas atomized Fe-6.5%Si.

Compared to pure Fe-6.5% Si, the advantages of this new material are higher magnetic saturation and high component density similar to that of pure Somaloy 110i 5P, as well as easy manufacturing procedures, *i.e.,* the compaction pressure is low or moderate (800-1200 MPa vs. 1200-2000 MPa for pure FeSi) which reduces production costs. The material displays high frequency losses similar to that of Somaloy 110i 5P+Sendust, but due to the high saturation and density of the Somaloy 110i 5P/FeSi components, the low frequency core losses are further reduced. In this study, this new material concept will also be compared to other inductor materials.

Key words:
Somaloy 5P
FeSi
Sendust
Soft Magnetic Composite
Inductor Materials
DC-bias

1. Introduction

Soft magnetic composite (SMC) materials are ferromagnetic powder particles coated with an electrically insulating layer. Using conventional PM compaction techniques, SMC components can be manufactured for electric drive systems and other inductive components designed for higher operating frequency applications [1-4].

In these applications, SMC materials offer several advantages over traditional laminated steel cores due to their unique three-dimensional (3D) isotropic ferromagnetic properties. They can enable flexible component design and assembly, and offer opportunities greatly reducing weight and production costs [5,6]. Components designed for motor applications should display good permeability, low core loss and a high mechanical strength, whereas in inductor applications good DC bias and high magnetic saturation, in addition to low core losses, are the most important features [7].

SMC materials are often based on pure iron particles. These materials have high magnetic saturation and are easy to process using traditional PM compaction techniques. The total core loss of these materials includes in-particle and component eddy current loss, and bulk hysteresis loss [7]. Depending on the application, it can be relatively easy to minimize the eddy current loss by changing the particle size and/or modifying the thickness of the insulating coating layer. The low eddy current loss is one of the main advantages of SMC materials in comparison to competing techniques, such as laminate steel [8-10]. However, during the compaction process plastic deformation of the particles introduce stress in the component, and this leads to a high hysteresis loss that has the potential to limit wider use of these materials. The key to lowering the hysteresis loss is to relieve the stresses through heat treatment. In order to achieve complete stress relief of the iron particles, the heat treatment temperature should reach temperatures above 600 °C and the limiting factor, which determines the allowable heat treatment temperature, is the thermal stability of the electrically insulating coating on the particles [11-13].

The Somaloy 5P materials previously developed by Höganäs AB, are water atomized iron powders with a multi-layer inorganic coating that is able to withstand heat treatment temperatures up to 650-700°C [7]. The Somaloy *i*-series are materials suitable for inductor applications or high frequency motor applications. The core losses of 5P materials are obviously lower than traditional SMC materials, and the main reason is the decreased coercivity of the material. However, compared to other soft magnetic alloys such as Sendust and FeSi, the hysteresis losses are still relatively high. The advantage of materials with high content of pure iron powder is that it rather easily can be compacted to very high density levels which, in combination with gapping in the application, can result in very good DC-Bias.

Gas atomized Fe-6.5% Si powders have lower losses compared to pure iron due to low hysteresis and low in-particle eddy currents. However, the magnetic saturation, while higher than Sendust, is still low compared to pure iron at a given density. In addition, these particles are hard and spherical, so therefore require high compaction pressures (1200-2000 MPa) and often display low strength for both green and heat-treated components. The low green strength of these materials can lead problems in full-scale production, with a possible decrease in productivity due to the high scrap-rate. In some applications binders have to be used, which will further decrease the magnetic saturation [13].

In this study, we investigate a concept which combines the high saturation induction of pure iron particles with low loss gas atomized Fe-6.5%Si particles. Mixtures of Somaloy 110i 5P with varying amounts of FeSi will be evaluated, and since the SMC concept is inherently very flexible, the effect of the lubricant system, compaction process and heat treatment, will also be investigated in order to learn more about the powder composition and process parameters. The obtained results will then be compared to reference inductor materials.

2. Experimental Procedure

Gas atomized Fe-6.5% Si powder (10-50 wt% addition) was mixed with the base powder Somaloy 110i 5P and lubricant. Prior to mixing, the FeSi powder was coated with an inorganic coating according to Ref 14, in order to maintain low specific resistivities of the components. Components for evaluation of magnetic properties and material strength (magnetic toroids 55x45x5mm and IE-bars, respectively) were compacted at different pressures and die temperatures, as can be seen in Table 1. After compaction, the components were heat-treated using standard 5P heat treatment with peak temperatures in the 675-700ºC range. The atmosphere was either pure nitrogen or nitrogen with a low oxygen content (up to 5000 ppm) [15].

Transverse Rupture Strength (TRS) was measured according to ISO 3995 and the specific electrical resistivity was measured on the ring samples by a four point measuring method. The toroid samples were wound with a 100 turn winding for drive and 100 + 20 turn windings for sense, where 100 turns and 20 turns were used for low and high frequency measurements, respectively. Low frequency core losses and B-H curves were measured using a Brockhaus hysterisisgraph 200, while an AMH200k was used to measure high frequency core losses.

Table 1. The experimental matrix investigated in this study.

Lubricant	Lub A	Lub 2
Amount of lubricant [wt%]	0.4	0.3-0.5
Die temperatures [°C]	RT-80	60-100
Compaction pressures [MPa]	800-1200	800-1200

3. Results and Discussion

Only a selection of the full data set will be presented in order to highlight the most important aspects of this study.

3.1 The optimum Somaloy 110i 5P/FeSi composition

Somaloy 5P materials are press-ready powders including an internal lubricating system, referred to as Lub A. In this system, the lubricant is actually part of the coating, and the best overall performance is obtained with a lubricant amount suitable for the selected iron particle size and a controlled temperature of the tool die [15]. For Somaloy 110i 5P, the recommended lubricant contents and die temperature are 0.4 wt% and 60 °C, respectively. The heat treatment of these materials requires an atmosphere of pure nitrogen or nitrogen with a small amount of oxygen. Lubricant burn-off and coating activation occurs at around 450°C, and the temperature is then increased to 650 °C for complete stress relief of the material.

Introducing the FeSi particles in the material matrix will of course alter the optimum process parameters slightly. For example, these particles requires higher peak temperatures in order to fully relax the material, and the hard and spherical nature of these particles necessitates a lubrication system with the potential to increase the green strength. Since the 5P coating is thermally stable up to 700°C, increasing the peak temperature in the heat-treatment cycle is fairly straight forward. In order to increase the green strength, an alternative lubrication system was also tested in this study.

Lubrication system

In powder metallurgy, the lubricant is very important, as it will affect the productivity, component quality, and tool life. For SMC materials, the function of the lubricant is to not only reduce the friction between the component and the die wall during compaction and ejection, but also to protect the coating during this process [7]. In that sense, the lubricant can be regarded as a part or the coating. Therefore, an optimized lubricant system does not only require optimizing the actual wt%-content in relation to the particle size, component size and geometry, and tool quality, but it requires a lubricant that provides a positive overall chemical interaction with the coating material.

In Figure 1 the green strength (GS) and TRS-values of heat-treated components obtained for mixes with varying contents of FeSi are shown. Two types of lubricants, Lub A and Lub B, were tested and the results shown in Figure 1 are for 0.4wt% lubricant contents. It can be seen that the use of Lub B resulted in significantly higher GS values, and that this effect becomes more pronounced as the die temperature increases. Similar overall trends in relation to GS and TRS were observed at 1000 and 1200 MPa. However, the increase in material strength after heat-treatment for the Lub B materials, when compared to Lub A materials, was progressively less pronounced as the compaction pressure increased. The lower material strength of heat-treated components for mixtures containing Lub B, shows that this lubrication system isn't interacting as well with the coating as Lub A.

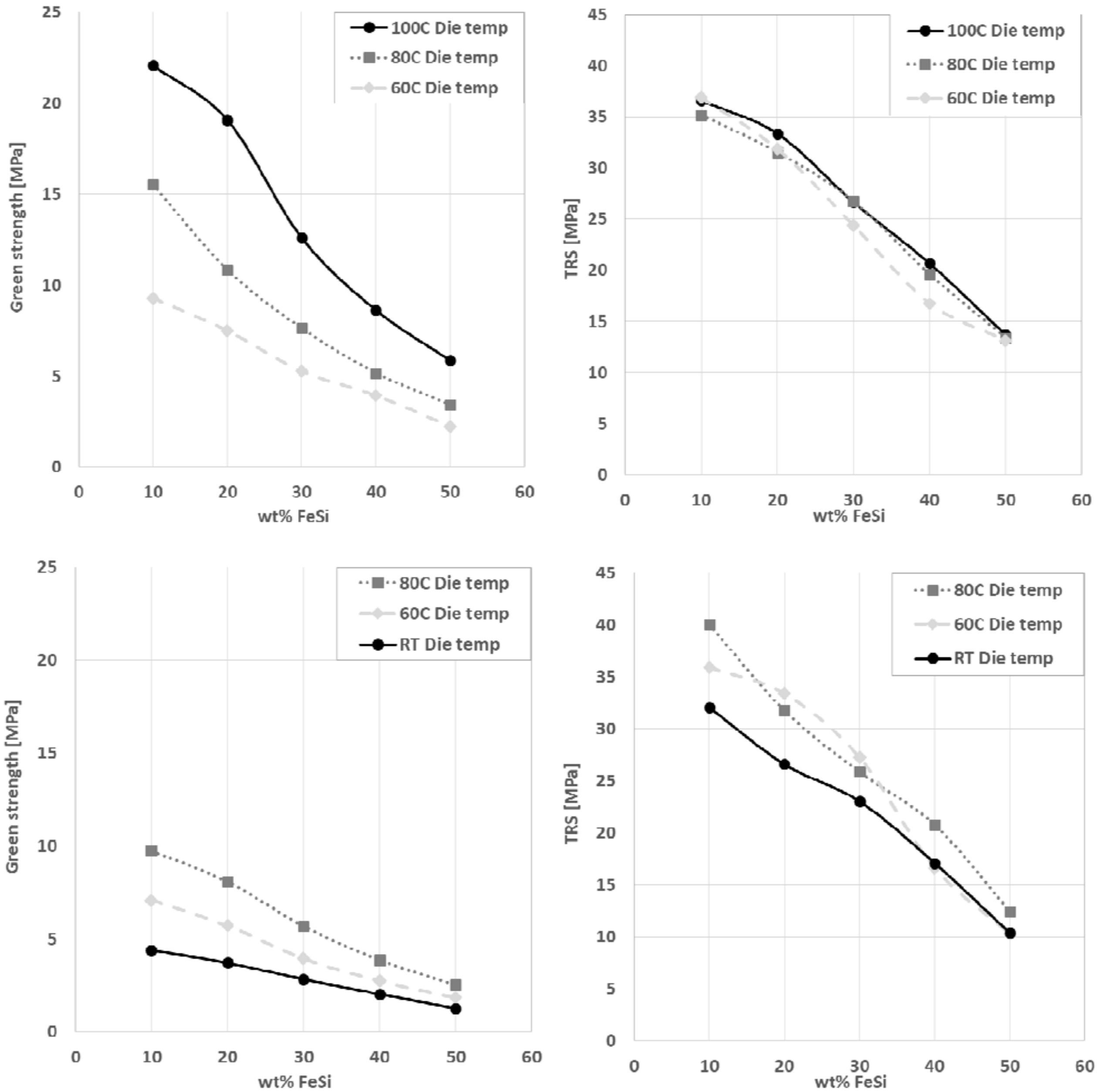

Figure 1. Green strength and TRS values obtained for materials with varying FeSi contents. The components were compacted at 800 MPa with 0.4 wt% lubricant content. Top panels: Lub B. Bottom panels: Lub A.

In Table 2, the specific resistivity and density of the magnetic toroid samples, compacted with a die temperature of 80 °C, are shown. The magnetic DC-properties of these samples can be found in Table 3. Looking at the results it can be concluded that the two lubrication systems included in this study provides similar compressibility and magnetic performance of the materials. However, a decrease in component resistivity could be observed for the Lub B mixes, when compared to the Lub A mixes, which is indicative of a slightly less favorable interaction between the lubricant and the coating. Nevertheless, given the significant increase in GS achieved using Lub B, it is concluded that this is the most suitable lubricant for the Somaloy 110i 5P/FeSi mixes.

Table 2. Resistivity and density obtained for magnetic toroids compacted at 80 °C.

FeSi [wt%]	Resistivity [μΩm]	Density [g/cm^3]	Resistivity [μΩm]	Density [g/cm^3]
	Lub A, 800 MPa		**Lub B, 800 MPa**	
10	>20000	7.26	>10000	7.23
20	>20000	7.20	>10000	7.18
30	>20000	7.14	>10000	7.11
40	>50000	7.06	>20000	7.04
50	>50000	6.98	>20000	6.95
	Lub A, 1000 MPa		**Lub B, 1000 MPa**	
10	>20000	7.31	>10000	7.28
20	>20000	7.29	>10000	7.26
30	>20000	7.23	>10000	7.21
40	>50000	7.15	>20000	7.14
50	>50000	7.09	>20000	7.08
	Lub A, 1200 MPa		**Lub B, 1200 MPa**	
10	>20000	7.34	>10000	7.30
20	>20000	7.30	>10000	7.26
30	>20000	7.25	>10000	7.22
40	>50000	7.22	>20000	7.19
50	>50000	7.15	>20000	7.13

Table 3. Magnetic properties obtained for components compacted at 80 °C.

FeSi [wt%]	B @ 4kA/m [T]	B @ 10kA/m [T]	μmax	Hc @ 10 kA/m [A/m]	B @ 4kA/m [T]	B @ 10kA/m [T]	μmax	Hc @ 10 kA/m [A/m]
		Lub A, 800 MPa				**Lub B, 800 MPa**		
10	0.88	1.32	204.3	198.8	0.88	1.32	208.8	196.8
20	0.84	1.28	195.1	183.1	0.84	1.28	194.8	185.2
30	0.78	1.24	177.4	171.6	0.78	1.23	178.6	173.3
40	0.71	1.18	158.0	158.0	0.71	1.17	158.4	156.3
50	0.48	0.93	103.3	144.8	0.49	0.94	105.2	144.8
		Lub A, 1000 MPa				**Lub B, 100 MPa**		
10	0.91	1.35	212	194.7	0.88	1.33	202.6	195.7
20	0.85	1.30	197	183.9	0.86	1.31	197.2	182.6
30	0.83	1.29	188	169.2	0.82	1.28	187.9	172.7
40	0.77	1.24	171	158.8	0.78	1.24	174.4	161.3
50	0.51	0.99	112	144.3	0.59	1.08	128.2	151.5
		Lub A, 1200 MPa				**Lub B, 1200 MPa**		
10	0.91	1.37	213	192	0.86	1.33	197.0	194.6
20	0.88	1.33	201	181	0.84	1.31	191.4	181.2
30	0.84	1.31	191	167	0.81	1.28	181.1	173.4
40	0.80	1.27	179	159	0.79	1.26	176.2	160.5
50	0.54	1.04	118	143	0.64	1.15	138.1	148.8

Amount of FeSi

In this product we try to combine the best of two worlds, with the high density and high magnetic saturation of Somaloy 110i 5P, and the low coersivity and hysteresis losses of gas atomized FeSi. Naturally, there is an optimum mixture for the perfect balance of these properites. In order to find this mixture, the low and high frequency core losses should be examined in more detail. In Figure 2, the core losses of magnetic toroids with varying contents of FeSi and compacted at 80 °C are shown. These results clearly show a minimum in the core losses, for both high and low frequencies in both lubrication systems, with around 30-40 wt% FeSi added in the mixture, indicating that this addition renders the optimum composition for this material. In addition, as can be seen in Figure 2, increasing the compaction pressure from 800 MPa to 1000 MPa will significantly decrease the losses irrespective of the amount of FeSi added to the mixture. This effect is less pronounced when the compaction pressure is increased further to 1200 MPa.

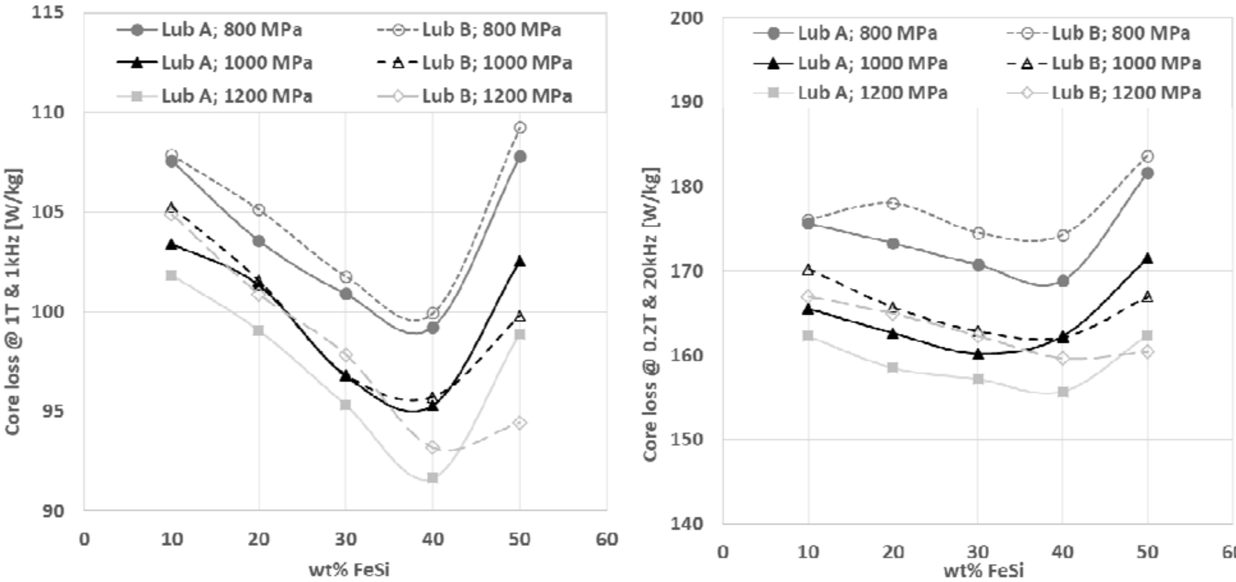

Figure 2. Core losses obtained for materials with varying FeSi contents. 0.4 wt% lubricant; low and high frequency in the left and right panel, respectively.

3.2 Comparison to other inductor materials

In the previous section, the optimum composition of the Somaloy 110i 5P/FeSi mix, with respect to core losses, was identified as containing 30-40 wt% gas atomized FeSi. This was mostly due to its positive contribution to the material GS with 0.4 wt% Lub B chosen as the lubrication system. In the following text, the selected composition of Somaloy 110i 5P and FeSi will be compared to both pure Somaloy 110i 5P, and a mixture of Somaloy 110i 5P and Sendust (25 wt% added). Even at this amount of Sendust added, the magnetic saturation was sigificantly lower and the core losses higher than that of the FeSi mixes. Therefore, higher amounts of Sendust in the reference mixture were not tested.

The B-H curves of the Somaloy 110i 5P/FeSi mix, compacted at 1000 and 1200 MPa with 80 °C on the die, together with the reference materials are shown in the top panel of Figure 3. In the bottom panel, the core losses obtained for high and low frequency are shown. It can be seen that, especially for the higher compaction pressure, the Somaloy 110i 5P/FeSi mix has a magnetic saturation close to that of pure Somaloy 110i 5P and the DC-bias is improved when compared to the pure iron reference material. The new material displays high frequency losses similar to that of the Somaloy 110i 5P/Sendust mix. In addition, due to the high saturation and density of the Somaloy 110i 5P/FeSi components, the low frequency core losses are further reduced, when compared to both reference materials. Moreover, one true advantage of this mix, is the possibility to compact complicated 3D structures, such as pot-cores.

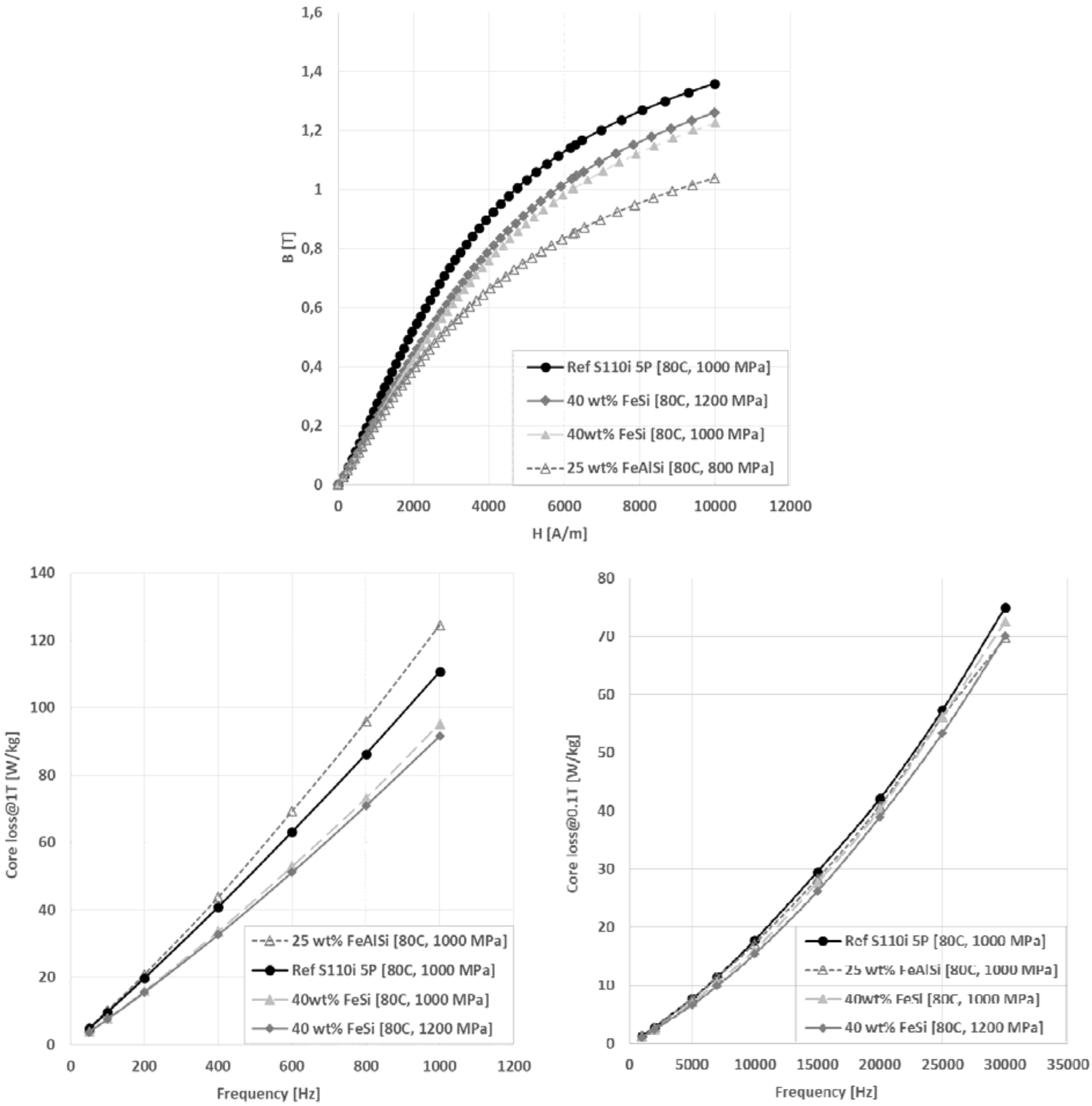

Figure 3. Top panel: BH-curves of the optimal Somaloy 110i 5P/FeSi composition (40 wt% FeSi and 0.4 wt% Lub B) and selected inductor reference materials. Bottom panel: Low and high frequency core losses obtained for these materials.

4. Conclusions

The ideal SMC material for inductor applications should have high induction, low losses and good DC-bias. In addition, it should be easily processed into a 3D net shape with high density in order to take full advantage of the isotropic nature of the material. In this study, a new inductor material has been demonstrated, which utilizes the high magnetic saturation and thermally stable coating material in Somaloy 110i 5P in combination with low coersivity gas atomized FeSi.

The optimum amount of FeSi, lubricant content, compaction pressure and die temperature has been evaluated for the best magnetic and mechanical performance. The results show that a material with a 30-40wt% FeSi content and 0,4 wt% Lub B internal lubricant system performed well. This material isalso easy to process, with low compaction pressures and high green strengths, and displays low core losses in both the high and low frequency ranges. It is recommended that this material should be compacted at a pressure of 1000 MPa or higher with a die temperature of around 80 □C. The compacted component should then be heat-treated with a two step process in an atmosphere of pure nitrogen, or nitrogen with a low amount of oxygen, similar to heat treatment of standard 5P materials.

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