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Loss separation in soft magnetic composites

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Abstract

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26 We report and discuss significant results on the magnetic losses and their frequency dependence
27 in soft magnetic composites. Two types of bonded Fe-based materials have been characterized at
28 different inductions from DC to 10 kHz and analyzed by extending the concept of loss separation
29 and the related statistical theory to the case of heterogeneous materials. Starting from the
30 experimental evidence of eddy current confinement inside the individual particles, the classical loss
31 component is calculated for given particle size distribution. Taking then into account the
32 contribution of the experimentally determined quasi-static (hysteresis) loss, the excess loss
33 component is obtained and quantitatively assessed. Its behavior shows that the dynamic
34 homogenization of the magnetization process with frequency, a landmark feature of magnetic
35 laminations, is restrained in these materials. This results into a partial offset of the loss advantage
36 offered by the eddy current confinement.

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I. INTRODUCTION

Three-dimensional flux paths and high frequencies are ubiquitous in modern electrical machines [1][2] and laminated cores may often prove inadequate. In fact, while inhibited from out-of-plane magnetization, soft magnetic laminations show a rapid increase of the power loss and fall into skin effect phenomena in the presence of harmonics and/or high working frequencies [3] [4]. Soft magnetic composites (SMCs) are therefore often proposed as convenient substitutes, their use appearing especially suited for devices like permanent magnet, claw-pole, and axial flux machines. While many literature efforts in these materials have been devoted to preparation methods and microstructural studies, with the aim of improving their manufacturing process, their mechanical properties, and their magnetic behavior[5][6], the analysis of the magnetic properties has mostly been performed on qualitative grounds [7][8], aiming at rapid exploitation in SMC machine core modeling [9]. For example, the important problem of loss calculation in such materials has been approached by use of polynomial interpolation methods [10][11], which are not accurate enough to predict the loss under highly distorted induction waveforms. De Wulf, et al. [12] have resorted to the concept of loss separation and attempted to apply Bertotti's statistical theory [13] to the frequency dependence of the energy loss in different types of SMCs. Their study was, however, limited to the maximum frequency of 100 Hz and their calculations disregard the actual heterogeneous structure of the material.

In this paper we present significant new results on the energy losses and their frequency dependence (DC – 10 kHz) in commercial soft Fe bonded composites. The experiments show that the sample cross-sectional area negligibly affects the loss at all frequencies. The classical loss component is therefore calculated for eddy current paths confined within the grains and the loss decomposition, leading to the determination of the hysteresis and excess losses, is accordingly performed. The excess loss is observed to depend on frequency in a quasi-linear fashion, in contrast with the square-root law usually observed in magnetic laminations. This provides evidence for correspondingly weakened dynamic homogenization of the magnetization process, ensuing from

68 combination of strong internal demagnetizing effects and lack of long-range eddy currents.

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70 I. EXPERIMENTAL RESULTS AND DISCUSSION

71 Two commercial SMCs (Somaloy Prototyping and Somaloy 110i1P) have been investigated. The
72 first one (Material A) has the following physical properties: density $\delta = 7450 \text{ kg/m}^3$, electrical
73 resistivity $\rho = 2.80 \cdot 10^{-4} \text{ }\Omega\text{m}$, average particle size $\langle s \rangle = 114 \text{ }\mu\text{m}$. The second material (B) has quite
74 smaller particle size ($\langle s \rangle = 29.5 \text{ }\mu\text{m}$) and lower filling factor (density $\delta = 7260 \text{ kg/m}^3$, electrical
75 resistivity $\rho = 76 \cdot 10^{-4} \text{ }\Omega\text{m}$). Ring samples of mean diameter 50 mm and 25 mm were prepared for
76 magnetic testing. The larger rings had cross-sectional area $S_1 = 5 \times 5 \text{ mm}^2$, the smaller ones $S_2 = 2.5$
77 $\times 2.5 \text{ mm}^2$. Hysteresis loop and loss measurements under sinusoidal induction were carried out,
78 starting from quasi-static conditions (5 Hz for A and 20 Hz for B), up to $f = 10 \text{ kHz}$ for peak
79 polarization values $J_p = 0.50, 1.0, 1.25 \text{ T}$. A broadband hysteresisgraph-wattmeter with digital
80 control of the induction waveform endowed with a 5kVA DC-20 kHz CROWN power amplifier
81 was employed. Sample heating was prevented by keeping the sample immersed in a water bath.

82 A remarkable outcome of these experiments is that the energy loss $W(f)$ does not depend, at all
83 frequencies, on the cross-sectional area of the sample (Fig. 1, SMC type A). The same occurs in the
84 SMC type B. This finding implies that grain-to-grain conductivity phenomena, either due to random
85 metallic contacts through the binder [14] or capacitive effects at high frequencies can be
86 disregarded from the viewpoint of losses. With the eddy current paths confined within the particles,
87 a good simplification is introduced in the loss analysis, because one can concentrate on the behavior
88 of the individual particles and their statistics. To start with, we calculate the classical loss
89 component W_{cl} , which in this case is the contribution that would originate if all particles were
90 magnetized at the same uniform rate imposed to the sample as a whole. Scanning electron
91 microscope images permit one to appreciate size and morphology of the particles and their
92 distribution. The cross-sectional area S_{part} of each particle is determined from a number of

93 micrographs using an image processing software. Their shape is irregular (Fig. 2), but, for the sake
 94 of calculation, they are approximated as rectangles. The width and length of these equivalent
 95 rectangles are identified by performing extended micrographic analysis and by taking the mean
 96 values of particle area and aspect ratio. The Poisson equation for the magnetic field is then solved
 97 by a finite element procedure, [12] in order to compute the eddy current loss in the rectangles. The
 98 results for materials A and B are shown in Figs. 3 and 4, respectively, where the decomposition of
 99 the measured loss $W(f)$ into the hysteresis W_{hyst} and excess $W_{exc}(f)$ loss components is put in
 100 evidence. W_{hyst} is an experimental quantity, obtained by extrapolating the measured $W(f)$ to $f=0$.
 101 The strong reduction of $W_{cl}(f)$ ensuing from the reduction of the particle size is apparent. By
 102 associating it to a concurring reduction of $W_{exc}(f)$, one gets that, in spite of higher W_{hyst} , the total
 103 loss $W(f)$ in the fine-grained SMC type B becomes lower than in the coarse-grained SMC type A
 104 beyond about 2 kHz.

105 As known, the excess loss arises because the dynamic magnetization process, like the
 106 quasi-static one, is inhomogeneous in nature. However, since the eddy-current counterfields become
 107 stronger with increasing frequency and they have to be compensated by the applied field in order to
 108 keep a given magnetization rate J_p , progressive homogenization of this process is concurrently
 109 expected. This concept is made quantitative in terms of active magnetic objects (MOs) and their
 110 frequency dependence by the statistical theory of losses [13], which provides the following general
 111 expression for the excess loss

$$112 \quad W_{exc}(J_p, f) = 2n_o V_o J_p \left(\sqrt{1 + \frac{16\sigma G S V_o}{n_o^2 V_o^2} f J_p} - 1 \right) \quad (1)$$

113 where $G = 0.1356$, S is the cross-sectional area of the sample, V_o is a parameter related to the
 114 distribution of the local pinning fields for the MOs, and n_o is the number of MOs that are
 115 simultaneously active within the sample cross-section under quasi-static magnetization. It is
 116 generally found in magnetic laminations that n_o is at most a few units [13]. A basic tenet of the
 117 theory is that the number of active MOs varies with frequency according to the linear law $n = n_o +$

118 H_{exc}/V_0 , where $H_{\text{exc}} = W_{\text{exc}}/4J_p$ is the excess field to be dynamically applied in order to counteract
 119 the mesoscopic (i.e. circulating close to the moving domain walls) eddy current fields. By taking the
 120 experimental $W_{\text{exc}}(f)$, as obtained by subtracting $W_{\text{hyst}} + W_{\text{cl}}(f)$ from the measured $W(f)$ values (see
 121 Figs. 3 and 4), the n versus H_{exc} behavior is obtained, as shown for the A and B type SMCs in Fig. 5
 122 for $J_p = 1\text{T}$. The experimental n_0 and V_0 values found in this way are introduced in Eq. (1) and the
 123 so calculated $W_{\text{exc}}(f)$, added to W_{hyst} and the previously obtained $W_{\text{cl}}(f)$, results into the fitting loss
 124 curve for $W(f)$ shown in Figs. 3 and 4. A striking result of this analysis is that n_0 is orders of
 125 magnitude larger than in soft magnetic laminations. n_0 is a quantity that refers to the whole cross-
 126 sectional area of the sample [13] and it appears here that the magnetization process in SMCs tends
 127 to simultaneously invest a large number of particles at the same time already at low frequencies. It
 128 can therefore be assumed that there should be at least one active magnetic object per particle at zero
 129 excess field (i.e. under quasi-static excitation). If we take the type A SMC sample with $S = 25\text{ mm}^2$
 130 and average grain-size area $\langle s \rangle = 0.0130\text{ mm}^2$, one gets the mean number of particles $\langle n_{\text{part}} \rangle$ in
 131 the sample cross section $\langle n_{\text{part}} \rangle = 1924$, close to the number n_0 of MOs (Fig. 5). For this material,
 132 the observed dependence of n on the excess field (i.e. frequency), shown for $J_p = 1.0\text{ T}$ in Fig. 5,
 133 suggests that each particle should contain a few MOs, which will be dynamically activated on
 134 increasing the frequency. The type B SMC shows a remarkably higher n_0 value, as expected from a
 135 correspondingly lower grain size. In both cases we observe that the condition $n_0 \gg H_{\text{exc}}/V_0$ is
 136 approximately satisfied in a good part of the investigated frequency range. A first order expansion
 137 of Eq. (3) correspondingly provides $W_{\text{exc}} \sim f$. This contrasts with usual $H_{\text{exc}}/V_0 \gg n_0$ condition
 138 already found at low frequencies in magnetic laminations [13], which leads to the typical $W_{\text{exc}} \sim$
 139 $f^{1/2}$ law.

140 III. CONCLUSIONS

141 The measurement of magnetic losses from DC to 10 kHz in commercial soft magnetic
 142 composite materials and the analysis of the results -centered on the concept of loss decomposition-
 143 highlights peculiar features of these materials. It is verified that the eddy currents are by and large

144 hindered from grain-to-grain circulation at all frequencies, with ensuing benefits from the viewpoint
145 of energy dissipation. This fact permits one to simplify the problem of loss calculation, whereby the
146 classical loss component can be analytically derived from knowledge of the distribution of the
147 particle size. A general formulation for the excess loss component, as provided by the statistical
148 theory of losses, can then be applied and shown to describe the experimental results and their
149 dependence on frequency. It is induced that the magnetization process in SMCs is characterized by
150 a good degree of homogenization already at very low magnetizing frequencies. The lack of
151 macroscopic eddy current patterns and the related counterfields eventually results, however, into a
152 faster than usual increase of the excess loss component with frequency and into its correspondingly
153 good contribution to the total loss up to the maximum investigated frequency of 10 kHz.

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Figure captions

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187 Fig. 1: Energy loss versus frequency measured at peak polarization values $J_p = 0.5$ T, 1.0 T, 1.25 T in the
188 type A soft magnetic composite ($\delta_{\text{proto}}=7450$ kg/m³). The results are obtained on two ring samples of cross-
189 sectional areas $S_1 = 5 \times 5$ mm² and $S_2 = 2.5 \times 2.5$ mm², respectively.

190 Fig. 2: Micrograph for the type B SMC. The classical eddy current loss component $W_{\text{cl}}(f)$ is calculated
191 assimilating this structure with an array of rectangular grains.

192 Fig. 3: DC-10 kHz loss separation at $J_p = 1.0$ T in the SMC type A. The energy loss $W(f)$ (open symbols) is
193 measured under controlled sinusoidal flux. The continuous fitting line is obtained by adding to the
194 experimental hysteresis loss W_{hyst} the classical loss $W_{\text{cl}}(f)$, calculated with finite elements.

195 Fig. 4: Same as Fig. 3 for the SMC type B.

196 Fig. 5: Number of active magnetic objects n versus the excess field $H_{\text{exc}} = W_{\text{exc}}/4J_p$ at $J_p = 1.0$ T in the two
197 investigated SMCs. The straight lines provides best fitting with the predicted relationship $n = n_0 + H_{\text{exc}}/V_0$.

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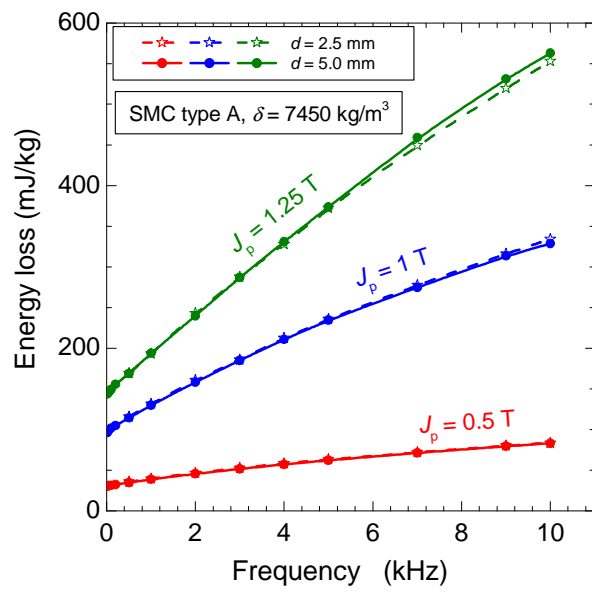


Fig. 1

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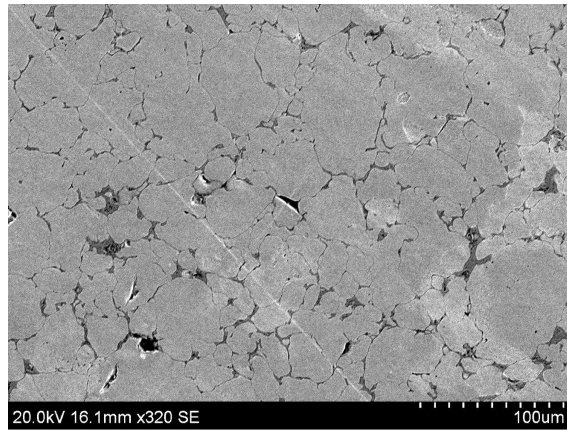


Fig. 2

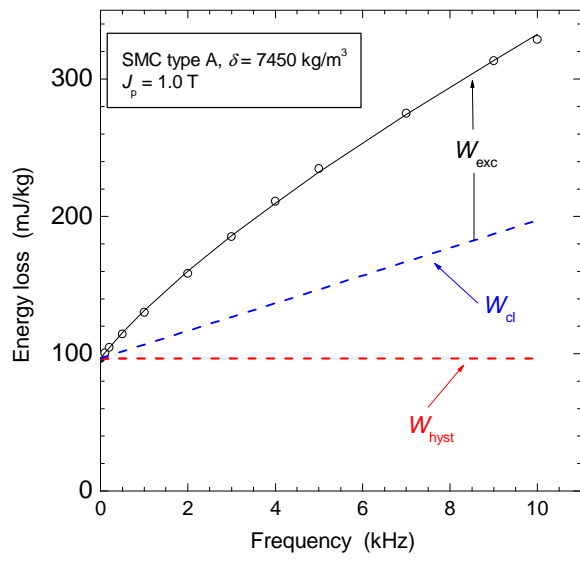
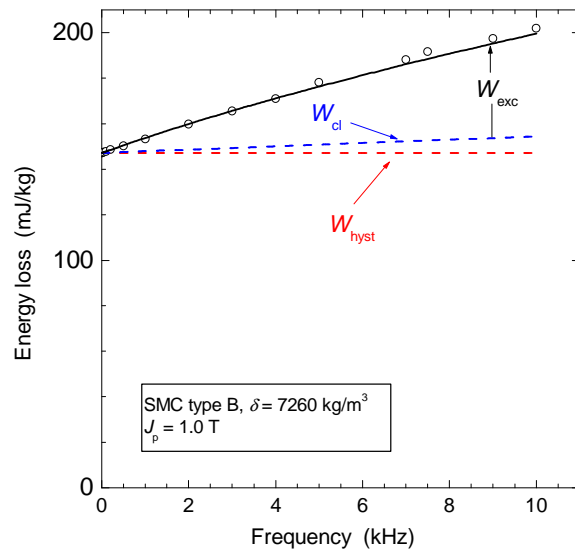


Fig. 3

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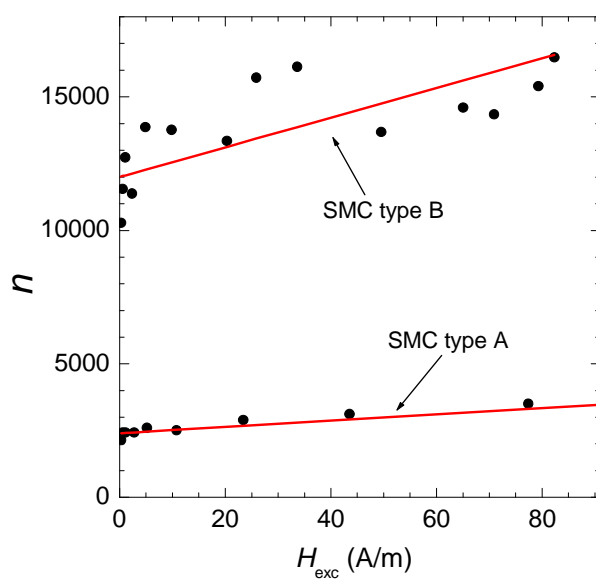


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Fig. 4

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Fig. 5