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Classical eddy current losses in Soft Magnetic Composites

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1 Abstract

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2 This paper deals with the problem of loss evaluation in Soft Magnetic Composites (SMC), focusing
3 on the classical loss component. It is known that eddy currents can flow in these granular materials at
4 two different scales, that of the single particle (microscopic eddy currents) and that of the specimen
5 cross-section (macroscopic eddy currents), the latter ensuing from imperfect insulation between
6 particles. It is often argued that this macroscopic loss component can be calculated considering an
7 equivalent homogeneous material of same bulk resistivity. This assumption has not found so far clear
8 and general experimental validation. In this paper, we discuss energy loss experiments in two different
9 SMC materials, obtained using different binder types, and we verify that a classical macroscopic loss
10 component, the sole size-dependent term, can be separately identified. It is also put in evidence that,
11 depending on the material, the measured sample resistivity and the equivalent resistivity entering the
12 calculation of the macroscopic eddy currents may not be the same. A corrective coefficient is therefore
13 introduced and experimentally identified. This coefficient appears to depend on the material type only,
14 the role of sample shape and/or cross-sectional area being irrelevant. An efficient way to calculate the
15 macroscopic classical loss in these materials, based on a minimum set of preliminary experimental
16 results, is thus provided. In this way, a reliable procedure for loss separation, whatever the sample size,
17 can be implemented.

18

19 **Introduction**

20 Soft Magnetic Composites (SMC) are of interest in modern electrical engineering applications.
21 Their isotropic magnetic and thermal behavior provides a clear advantage for machines with 3D flux
22 paths, like axial flux machines [1][2], or claw pole generators [3].

23 The loss separation concept, associated with the Statistical Theory of Losses (STL) [4], is known to
24 efficiently assess the loss phenomenology in soft magnetic laminations. Its extension to SMC is,
25 however, far from simple, because one has to deal with an inhomogeneous granular structure, where
26 eddy currents (e.c.) flow at two different scales: the scale of the single particle (microscopic e.c.), and
27 the scale of the whole sample (macroscopic e.c., due to intergrain conductivity) [6][7][8]. The
28 correspondingly measured bulk resistivity is often considered in the macroscopic eddy current
29 calculations, assuming an equivalent homogeneous material. It has been suggested that microscopic
30 and macroscopic e.c. can be associated with microscopic and macroscopic classical loss components,
31 respectively [6]. Although a certain dependence of the total dynamic loss on the bulk resistivity has
32 been shown [9], no clear experimental evidence of the separation between macroscopic and
33 microscopic classical losses has been provided so far. At the same time, the assumed link between the
34 measured material resistivity and the macroscopic e.c. has not been supported by experimental
35 observations.

36 It was previously shown [10] that loss separation according to STL could be carried out in small and
37 highly resistive SMC samples, where the macroscopic eddy currents are negligible. This appears,
38 however, a substantial restriction when looking at a reliable loss prediction in electrical equipments
39 using SMC [11]. In this paper, this limitation is overcome, by considering different SMC samples of
40 various sizes using either organic or inorganic binders, with resistivity values spanning several orders
41 of magnitude. We start by putting in evidence the dependence of the specific dynamic loss on the
42 sample cross-sectional area. The loss component dependent on the sample size is singled out and found
43 to linearly depend on frequency, thereby justifying its assimilation to a classical loss. The problem of

44 the relation between this macroscopic classical loss and the measured sample resistivity is discussed,
45 introducing a coefficient in the loss formulae that takes into account the grain-to-grain eddy current
46 percolation across random contacts. This theoretical framework is validated showing that the corrective
47 coefficient exclusively depends on the material type, regardless of the sample size. This provides an
48 efficient tool to make full loss decomposition in SMC, as discussed in the last part of the paper.

49 I. EXPERIMENTAL

50 A. Samples

51 The experiments presented in this paper have been carried out on several samples of two SMC
52 materials, herein called SMC_1 and SMC_2 , produced from a high purity iron powder ATOMET 1001HP
53 [12] provided by Quebec Metal Powders (QMP). The particles in the SMC_1 and SMC_2 materials are
54 insulated by means of organic and inorganic binder, respectively. The SMC_1 material is heat-treated at
55 low temperature (1 hour at 160°C), so as to improve the mechanical properties (e.g. fracture strength)
56 without damaging the organic insulator [13]. A higher-temperature treatment (1 hour at 425°C), as
57 permitted by the inorganic insulator, is applied to the SMC_2 material, bringing about a slight reduction
58 of the hysteresis (DC) loss contribution [13].

59 The samples are delivered as rings with rectangular cross-section (outside diameter 52.6 mm, inside
60 diameter 43.8 mm). Three different ring thicknesses have been considered: $t_1 = 5$ mm, $t_2 = 9$ mm, $t_3 =$
61 13 mm. Type and geometry of each sample are here identified as SMC_i-t_j ($i = 1, 2$, and $j = 1, 2, 3$). The
62 compaction pressure was in all cases $p = 600$ MPa, resulting, however, in increased material density
63 with decreasing sample thickness, as summarized in Table 1.

64 B. Resistivity measurements

65 In order to overcome the difficulties and ambiguities associated with the conventional four-point
66 resistivity measurement [8][14], an indirect method, where the toroidal sample is used as the secondary
67 winding of a transformer, has been adopted [15]. The results, reported in Table 1, show that the

68 resistivity of SMC_2 (inorganic binder) is more than one order of magnitude smaller than the one of
69 SMC_1 (organic binder). It is noted that different samples of a given material do not exactly exhibit the
70 very same resistivity, because the manufacturing process is not perfectly reproducible.

71 **II. MODELING THE MACROSCOPIC EDDY CURRENT LOSSES**

72 *A. Macroscopic eddy current losses*

73 The magnetic characterization of the ring specimens is performed under controlled sinusoidal
74 polarization (peak value $J_p = 1\text{T}$) from DC to 10 kHz with a calibrated hysteresisgraph-wattmeter, as
75 described in [16]. The experiments show (see Fig. 1 for SMC_2 , a similar behavior being observed in
76 SMC_1) that the specific loss in SMC materials depends on the material cross-sectional area (i.e., ring
77 thickness). To explain this phenomenon, it is often assumed [6][7] that the observed losses in SMC
78 samples are due to physical effects occurring upon two different scales: a) the microscopic loss, due to
79 the e.c. circulating within the individual iron particles; b) the macroscopic classical loss, due to the e.c.
80 flowing from particle to particle thanks to imperfections in particle insulation and describing
81 macroscopic patterns. However, no clear experimental evidence for effective role of these eddy
82 currents has been provided so far and there is no consensus on the underlying assumptions [17][18]. In
83 the following, we will provide evidence for a loss contribution depending on the sample cross-sectional
84 area that appears to proportionally depend on frequency, as expected for a classical loss component.

85 In order to single out the contribution to the specific loss depending on the sample cross-section
86 (W_{MAC}) from the one occurring upon the scale of the single particle (the microscopic loss W_{MIC}), the
87 loss difference measured in samples differing only for their size is considered. We thus write,
88 considering two sizes (a) and (b): $\Delta W^{(a,b)} = W^{(a)} - W^{(b)} = W_{MAC}^{(a)} - W_{MAC}^{(b)}$. Fig. 2 and Fig. 3 show the
89 differences ΔW measured between SMC_{1-t_3} and SMC_{1-t_1} , and SMC_{2-t_3} and SMC_{2-t_1} , respectively.
90 Similar results are obtained in other samples. ΔW linearly depends on frequency, thereby showing that
91 the macroscopic loss contribution is classical in nature.

$$\Delta W^{(a,b)} = W^{(a)} - W^{(b)} = W_{\text{class,MAC}}^{(a)} - W_{\text{class,MAC}}^{(b)} \quad (1)$$

92 We can thus generally write for the total specific loss $W(J_p, f) = W_{\text{class,MAC}}(J_p, f) + W_{\text{MIC}}(J_p, f)$. The
 93 microscopic part W_{MIC} was previously analyzed in the framework of STL [10] and was shown to be
 94 equal to the sum of an hysteresis contribution, an excess component, and a classical loss term deriving
 95 from the eddy currents circulating within the particles. This is defined as the microscopic classical loss
 96 $W_{\text{class,MIC}}$.

97 *B. Link between the macroscopic classical loss component and the sample resistivity*

98 It is frequently assumed that the measured material resistivity can be directly used for the macroscopic
 99 loss computation, assuming an equivalent homogeneous material [6][7]. But the link between sample
 100 resistivity and macroscopic classical loss is not obvious, because, as shown in [19], percolation due to
 101 random contacts between particles plays a role in highly compacted samples and interpretation of the
 102 experiments calls for a specific model of conduction by random contacts [19]. But this model requires
 103 considerable computational workload and a simpler approach is proposed here by introducing the
 104 notion of equivalent resistivity for the loss $\rho^{(\text{loss})}$, i.e. the resistivity which would produce, in an
 105 homogeneous sample, the same macroscopic loss observed in the SMC. Due to percolation, $\rho^{(\text{loss})}$ is
 106 expectedly different from the measured resistivity ρ , but we assume that proportionality exists, so that
 107 we can write $\rho^{(\text{loss})} = Q^{(\text{loss})} \cdot \rho$, with $Q^{(\text{loss})}$ a phenomenological coefficient. It is verified that $Q^{(\text{loss})}$
 108 depends only on the type of material and can be obtained comparing two samples with different cross-
 109 sectional area. Starting in fact from the calculation of eddy currents in a rectangular domain [10], we
 110 consider a ring sample with rectangular cross-section (thickness t , width ΔR , cross-sectional area $S_c =$
 111 $t \cdot \Delta R$) and we obtain the macroscopic classical loss as:

$$W_{\text{class,MAC}}(J_p, f) = 2\pi^2 \frac{1}{\delta} \frac{1}{Q^{(\text{loss})} \rho} K_{\text{shape}} \left(\frac{\Delta R}{t} \right) \cdot S_c \cdot J_p^2 f \quad [\text{J/kg}] \quad (2)$$

112 where the parameter K_{shape} , which depends only on the width-to-thickness ratio $\Delta R / t$, is computed
 113 using a finite element method (it can be shown that the skin effect at the scale of the single particle is

114 negligible, implying that K_{shape} is independent of frequency). Comparing two samples (a) and (b) of the
 115 same material, Eq. (2) can be written as:

$$\Delta W^{(a,b)} = W^{(a)} - W^{(b)} = 2\pi^2 \frac{1}{Q^{(\text{loss})}} \left\{ \frac{K_{\text{shape}}^{(a)} S_c^{(a)}}{\delta^{(a)} \rho^{(a)}} - \frac{K_{\text{shape}}^{(b)} S_c^{(b)}}{\delta^{(b)} \rho^{(b)}} \right\} J_p^2 f \quad [\text{J/kg}] \quad (3)$$

116

117 C. Validation of the macroscopic loss model

118 In order to validate the macroscopic loss model, we show that the dimensionless coefficient $Q^{(\text{loss})}$ is
 119 independent of sample shape and size and is only material dependent. $Q^{(\text{loss})}$ is identified looking at the
 120 experimentally observed loss difference between SMC_{i-t_2} ($i = 1$ or 2) and SMC_{i-t_1} samples. In fact,
 121 since the experimental loss difference linearly depends on f , it is sufficient to adapt the coefficient
 122 $Q^{(\text{loss})}$ to get the observed behavior of $\Delta W^{(a,b)}$ versus f . We find $Q^{(\text{loss})} = 1$ for the material SMC_1 and
 123 $Q^{(\text{loss})} = 1.56$ for SMC_2 . Since $Q^{(\text{loss})} = 1$, the conventional approach invoking an equivalent
 124 homogeneous material [6][7] is acceptable in calculating $W_{\text{class,MAC}}(J_p, f)$ in the material SMC_1 . This
 125 implies that in the material with organic binder heat-treated at low temperature, eddy current
 126 percolation by intergrain random contacts does not play any role (the observed resistivity being that of
 127 the binder). On the other hand, in the material SMC_2 , heat-treated at higher temperature, percolation
 128 takes place and it is accordingly found that $\rho^{(\text{loss})}$ is higher than the measured resistivity [19]. This
 129 points to percolation as a mechanism affecting to different extent the current patterns involved with the
 130 conductivity measurements and the magnetic losses.

131 That the coefficient $Q^{(\text{loss})}$ is, to good approximation, material dependent only can be understood in
 132 terms of local character of the random interparticle contacts, making $Q^{(\text{loss})}$ independent of the cross-
 133 sectional area in sufficiently big samples. This is an important point in the practical use of this model.
 134 We observe in Fig. 2 and Fig. 3 the close behaviors of the experimental and the so calculated loss
 135 differences ΔW versus f in the ring samples SMC_{i-t_3} ($i = 1$ or 2) and SMC_{i-t_1} (the experimental ΔW
 136 observed at $f = 0$ being related to the uncertainty associated with the determination of this quantity for

137 the hysteresis loss component). The coefficient $Q^{(\text{loss})}$ can then be simply obtained, for a given material,
138 from the loss difference measured on two differently sized samples, an important result in view of loss
139 prediction in practical cores.

140 *D. Loss separation*

141 Once the macroscopic classical loss is known, it is possible to perform the loss decomposition. The
142 microscopic classical loss (i.e. the classical loss at the scale of the single particle $W_{\text{class,MIC}}$) is calculated
143 once the size distribution of the particles is obtained by micrographic inspection [10]. In the present
144 experiments, $W_{\text{class,MIC}}$ is the same in SMC_1 and SMC_2 (the same iron powder is employed). The excess
145 and hysteresis loss components can then be singled out from the total experimental loss W_{tot} (see [10]
146 for the detailed procedure). Fig. 4 and Fig. 5 present the results for SMC_{1-t_2} and SMC_{2-t_2} , respectively
147 (sinusoidal polarization, $J_p = 1\text{T}$). A striking difference in the macroscopic loss $W_{\text{class,MAC}}(J_p, f)$ between
148 the two materials is found, descending from the large difference in the measured resistivities (see Table
149 1). We note, in particular, that $W_{\text{class,MAC}}(J_p, f) \sim 15 \cdot W_{\text{class,MIC}}(J_p, f)$ in the SMC_{2-t_2} sample. This would
150 restrict the use of SMC_2 to low frequencies.

151 **III. CONCLUSION**

152 We have put in evidence the link between sample resistivity and macroscopic classical loss in two
153 different classes of commercial Soft Magnetic Composites. An equivalent resistivity for the magnetic
154 losses, taking into account the effect of random interparticle contacts and percolation, has been
155 introduced besides the measured resistivity. It is a material related quantity, independent of the sample
156 size, which provides a simplified route to loss calculation in practical magnetic cores.

157

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- 206

207 **Figure captions**

208 Fig. 1: Specific loss in SMC_2 samples (inorganic binder) as a function of frequency, for three
209 different thickness values t_1 , t_2 , and t_3 (sinusoidal polarization, $J_p = 1T$)

210 Fig. 2: Measured and calculated energy loss difference ΔW (sinusoidal polarization, $J_p = 1T$)
211 between the SMC_{1-t_3} and SMC_{1-t_1} samples. The predicted ΔW behavior is obtained from Eq. (3)
212 using the loss coefficient $Q^{(loss)}=1$.

213 Fig. 3: As in Fig. 2 for the samples SMC_{2-t_3} and SMC_{2-t_1} . The theoretical ΔW is obtained using
214 $Q^{(loss)} = 1.56$ in Eq. (3).

215 Fig. 4: Loss decomposition (sinusoidal polarization, $J_p = 1T$) in the SMC_{1-t_2} sample

216 Fig. 5: Loss decomposition (sinusoidal polarization, $J_p = 1T$) in the SMC_{2-t_2} sample

217

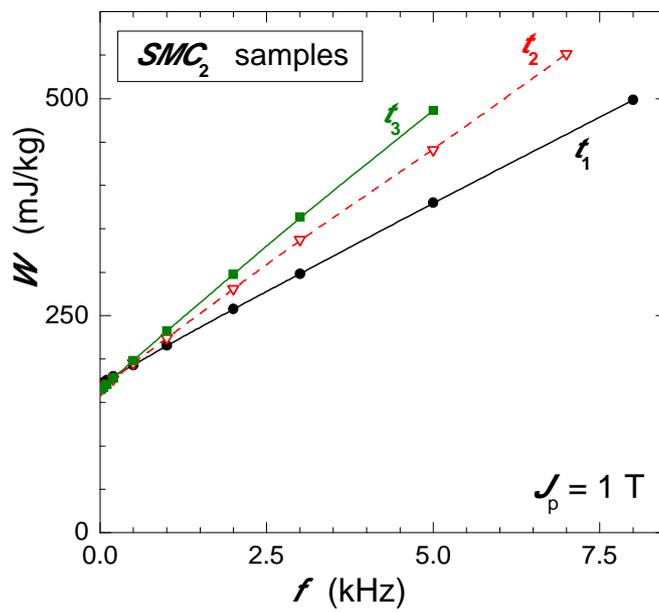
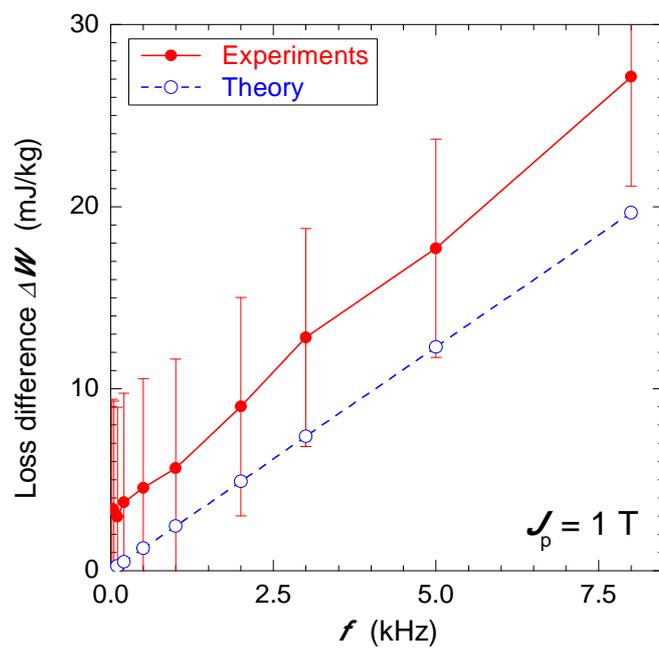


Fig. 1

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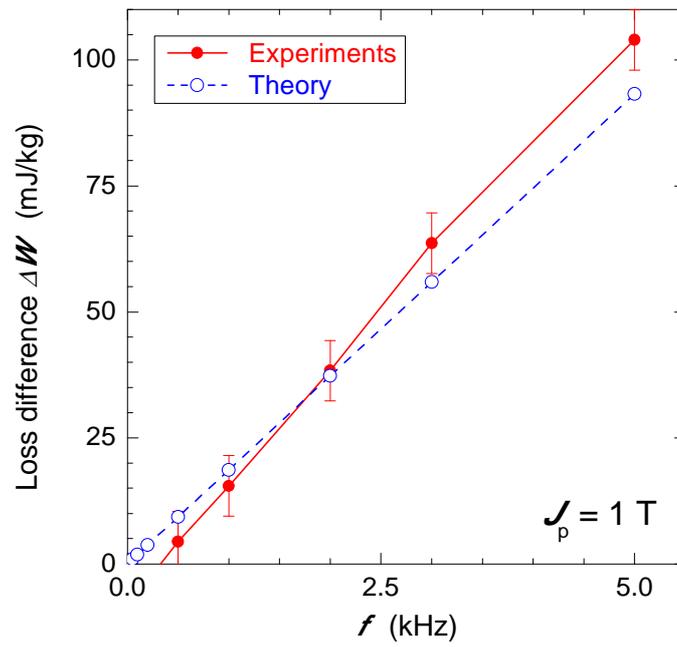
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Fig. 2

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Fig. 3

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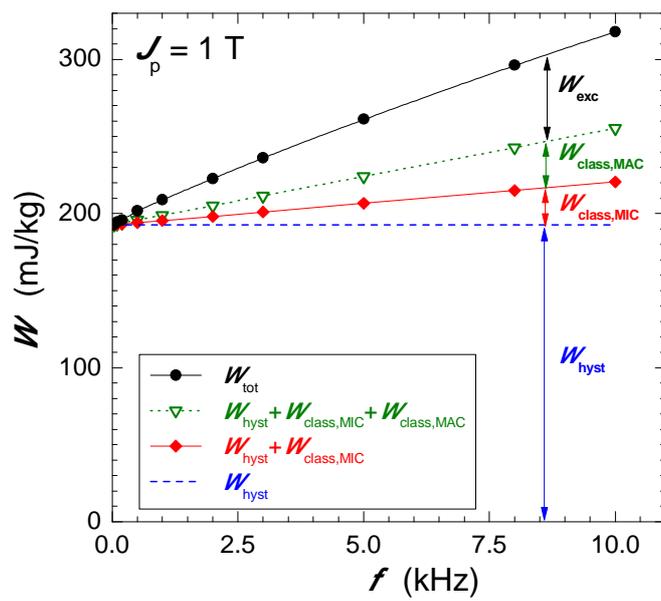


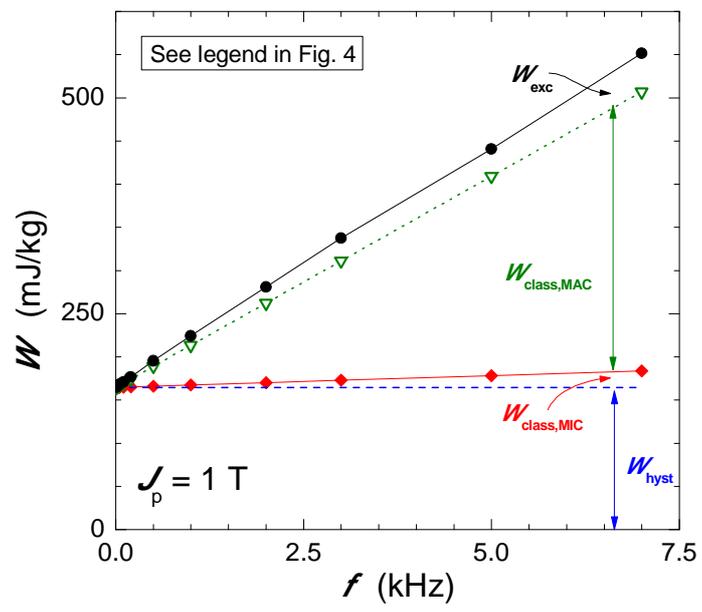
Fig. 4

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Fig. 5

238 **Table captions**

239 Table 1: Obtained densities δ and resistivities ρ for all materials (SMC_1 and SMC_2) and thicknesses

240 (t_1 , t_2 and t_3)

241

242 **Tables**
 243

Material	Axial Thickness (mm)		
	$t_1=5$	$t_2=9$	$t_3=13$
SMC_1	$\delta=7110 \text{ kg/m}^3$ $\rho=1590 \text{ }\mu\Omega\cdot\text{m}$	$\delta=7070$ $\rho=911$	$\delta=7010$ $\rho=1170$
SMC_2	$\delta=7130$ $\rho=48$	$\delta=7130$ $\rho=43$	$\delta=7100$ $\rho=45$

244 Table 1
 245