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Carlo Appino, Olivier de La Barrière, F . Fiorillo, Martino Lobue, Frédéric Mazaleyrat, Carlo Ragusa

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C. Appino[1], O. de la Barrière[2a], F. Fiorillo[1], M.LoBue[2], F. Mazaleyrat[2], C. Ragusa[3]

[1]Instituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy
[2]SATIE, ENS Cachan, CNRS, UniverSud, 61 av du President Wilson, F-94230 Cachan, France
[3]Dipartimento Energia, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy

Abstract

[a] Corresponding author: barriere@satie.ens-cachan.fr

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

Introduction

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

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

It was previously shown [10] that loss separation according to STL could be carried out in small and highly resistive SMC samples, where the macroscopic eddy currents are negligible. This appears, however, a substantial restriction when looking at a reliable loss prediction in electrical equipments using SMC [11]. In this paper, this limitation is overcome, by considering different SMC samples of various sizes using either organic or inorganic binders, with resistivity values spanning several orders of magnitude. We start by putting in evidence the dependence of the specific dynamic loss on the sample cross-sectional area. The loss component dependent on the sample size is singled out and found to linearly depend on frequency, thereby justifying its assimilation to a classical loss. The problem of the relation between this macroscopic classical loss and the measured sample resistivity is discussed, introducing a coefficient in the loss formulae that takes into account the grain-to-grain eddy current percolation across random contacts. This theoretical framework is validated showing that the corrective coefficient exclusively depends on the material type, regardless of the sample size. This provides an efficient tool to make full loss decomposition in SMC, as discussed in the last part of the paper.

I. **EXPERIMENTAL**

A. Samples

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

The samples are delivered as rings with rectangular cross-section (outside diameter 52.6 mm, inside diameter 43.8 mm). Three different ring thicknesses have been considered: t_1 = 5 mm, t_2 = 9 mm, t_3 = 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 compaction pressure was in all cases p = 600 MPa, resulting, however, in increased material density with decreasing sample thickness, as summarized in Table 1.

B. Resistivity measurements

In order to overcome the difficulties and ambiguities associated with the conventional four-point resistivity measurement [8][14], an indirect method, where the toroidal sample is used as the secondary winding of a transformer, has been adopted [15]. The results, reported in Table 1, show that the resistivity of SMC_2 (inorganic binder) is more than one order of magnitude smaller than the one of SMC_1 (organic binder). It is noted that different samples of a given material do not exactly exhibit the very same resistivity, because the manufacturing process is not perfectly reproducible.

II. MODELING THE MACROSCOPIC EDDY CURRENT LOSSES

A. Macroscopic eddy current losses

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

In order to single out the contribution to the specific loss depending on the sample cross-section (W_{MAC}) from the one occurring upon the scale of the single particle (the microscopic loss W_{MIC}), the loss difference measured in samples differing only for their size is considered. We thus write, 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 differences ΔW measured between SMC_1-t_3 and SMC_1-t_1, and SMC_2-t_3 and SMC_2-t_1, respectively. Similar results are obtained in other samples. ΔW linearly depends on frequency, thereby showing that the macroscopic loss contribution is classical in nature.

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

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 microscopic part W_{MIC} was previously analyzed in the framework of STL [10] and was shown to be equal to the sum of an hysteresis contribution, an excess component, and a classical loss term deriving from the eddy currents circulating within the particles. This is defined as the microscopic classical loss $W_{\text{class,MIC}}$.

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

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

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

where the parameter K_{shape}, which depends only on the width-to-thickness ratio $\Delta R / t$, is computed using a finite element method (it can be shown that the skin effect at the scale of the single particle is negligible, implying that K_{shape} is independent of frequency). Comparing two samples (a) and (b) of the same material, Eq. (2) can be written as:

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

C. <u>Validation of the macroscopic loss model</u>

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

That the coefficient $Q^{(\text{loss})}$ is, to good approximation, material dependent only can be understood in terms of local character of the random interparticle contacts, making $Q^{(\text{loss})}$ independent of the cross-sectional area in sufficiently big samples. This is an important point in the practical use of this model. We observe in Fig. 2 and Fig. 3 the close behaviors of the experimental and the so calculated loss differences ΔW versus f in the ring samples SMC_{i}-t_3 (i = 1 or 2) and SMC_{i}-t_1 (the experimental ΔW observed at $f = 0$ being related to the uncertainty associated with the determination of this quantity for the hysteresis loss component). The coefficient $Q^{(\mathrm{loss})}$ can then be simply obtained, for a given material, from the loss difference measured on two differently sized samples, an important result in view of loss prediction in practical cores.

D. Loss separation

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

III. CONCLUSION

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

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Figure captions

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

Fig. 2: Measured and calculated energy loss difference ΔW (sinusoidal polarization, J_p = 1T) between the SMC_1-t_3 and SMC_1-t_1 samples. The predicted ΔW behavior is obtained from Eq. (3) using the loss coefficient $Q^{(loss)}$=1.

Fig. 3: As in Fig. 2 for the samples SMC_2-t_3 and SMC_2-t_1. The theoretical ΔW is obtained using $Q^{(loss)}$ = 1.56 in Eq. (3).

Fig. 4: Loss decomposition (sinusoidal polarization, J_p = 1T) in the SMC_1-t_2 sample

Fig. 5: Loss decomposition (sinusoidal polarization, J_p = 1T) in the SMC_2-t_2 sample

Figures

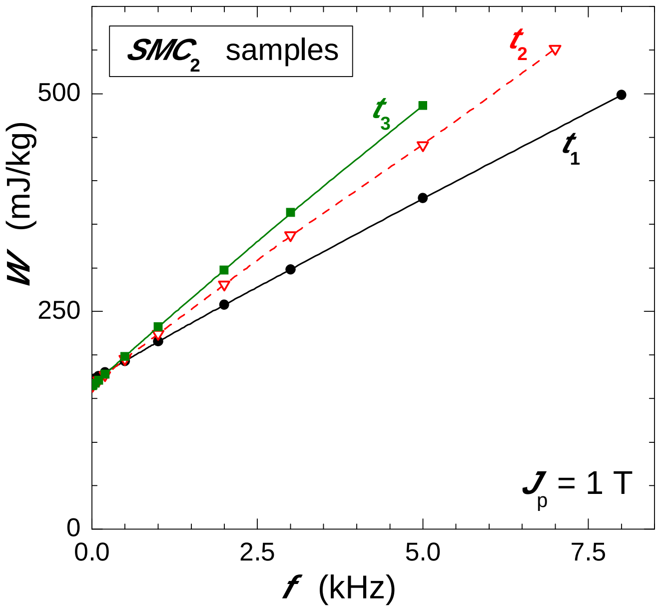


Fig. 1

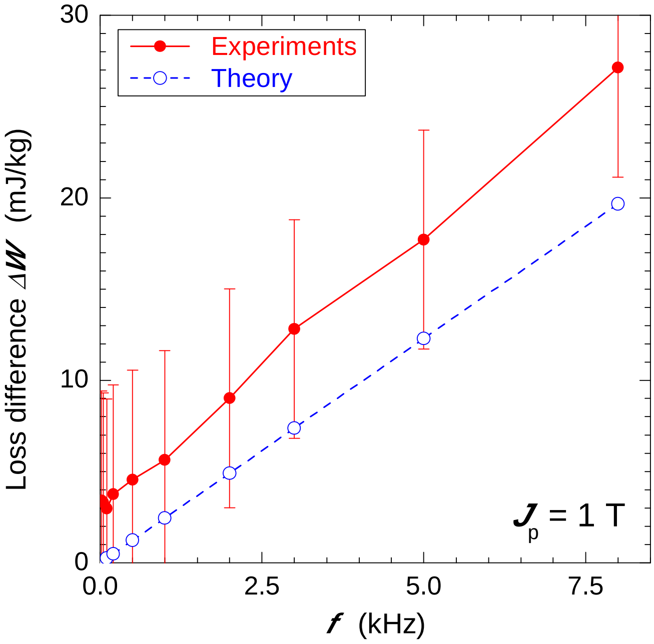

Experiments
Theory
J_p = 1 T
Loss difference ΔW (mJ/kg)
f (kHz)
0
10
20
30
0.0
2.5
5.0
7.5

Fig. 2

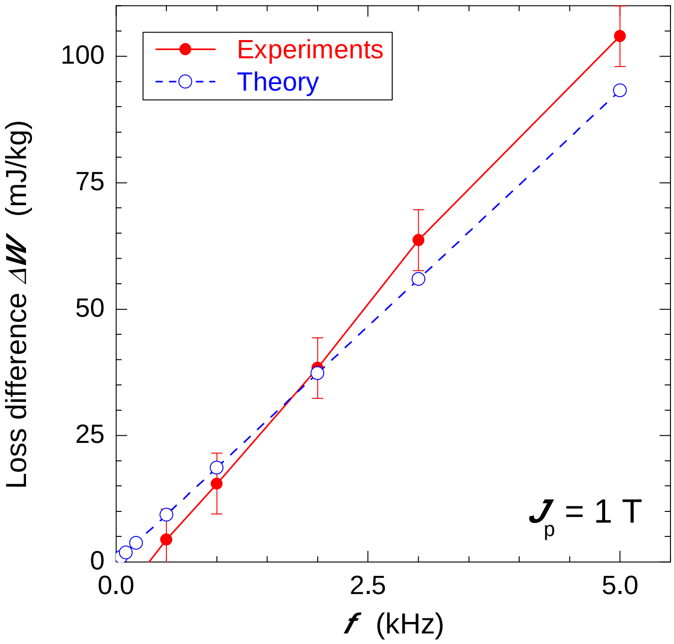
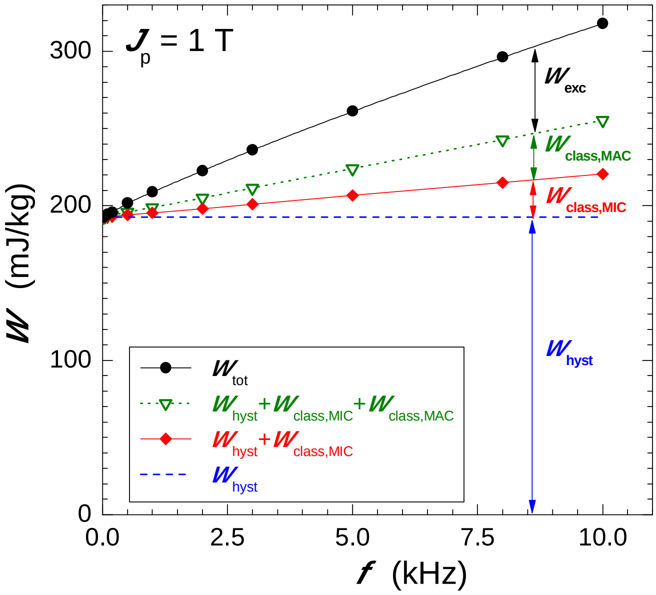

Experiments
Theory
Loss difference ΔW (mJ/kg)
f (kHz)
J_p = 1 T
0
25
50
75
100
0.0
2.5
5.0

Fig. 3



Jp = 1 T
300
200
100
0
W (mJ/kg)
0.0
2.5
5.0
7.5
10.0
f (kHz)
Wexc
Wclass,MAC
Wclass,MIC
Whyst
Wtot
Whyst+Wclass,MIC+Wclass,MAC
Whyst+Wclass,MIC
Whyst

Fig. 4

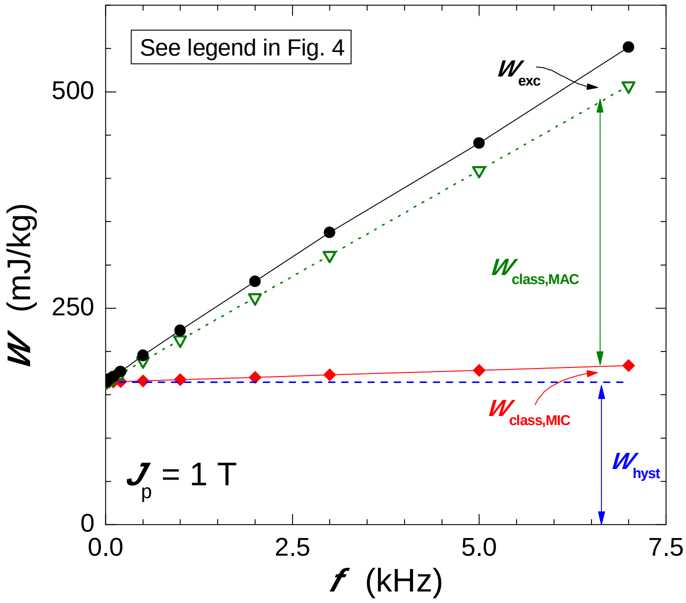

See legend in Fig. 4
W_exc
W_class,MAC
W_class,MIC
W_hyst
J_p = 1 T
W (mJ/kg)
f (kHz)
0
250
500
0.0
2.5
5.0
7.5

Fig. 5

Table captions

Table 1: Obtained densities δ and resistivities ρ for all materials (SMC_1 and SMC_2) and thicknesses (t_1, t_2 and t_3)

Tables

Material	Axial Thickness (mm)		
	t_1=5	t_2=9	t_3=13
SMC_1	δ=7110 kg/m^3 ρ=1590 μΩ·m	δ=7070 ρ=911	δ=7010 ρ=1170
SMC_2	δ=7130 ρ=48	δ=7130 ρ=43	δ=7100 ρ=45

Table 1