High-frequency rotational losses in different Soft Magnetic Composites (SMC)

Olivier de La Barrière, Carlo Appino, Carlo Ragusa, Fausto Fiorillo, F. Mazaleyrat, M. Lobue

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

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

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

Abstract

The isotropic properties of Soft Magnetic Composites (SMC) favor the design of new machine topologies and their granular structure can induce a potential decrease of the dynamic loss component at high frequencies. This paper is devoted to the characterization of the broadband magnetic losses of different SMC types under alternating and circular induction. The investigated materials differ by their grain size, heat treatment, compaction rate and binder type. It is shown that, up to peak polarization J_p = 1.25 T, the ratios between the rotational and the alternating loss components (classical, hysteresis, and excess) are quite independent of the material structural details, quite analogous to the known behavior of nonoriented steel laminations. At higher inductions, however, this is no more the case. It is observed, in particular, that the J_p value at which the rotational hysteresis loss attains its maximum, related to the progressive disappearance of the domain walls under increasing rotational fields, decreases with the material susceptibility.

I. INTRODUCTION

Embedded applications, such as hybrid vehicles or aircraft systems, are a challenge for machine designers. Indeed, the mass of these systems, and then the actuator torque density, are crucial parameters. Possible solution call either for the increase of the actuator working frequency, in order to improve the torque density [1], or the design of non-conventional machine topologies such as claw pole machines [2]. For both alternatives, the technological limitations of conventional laminated magnetic materials may be reached. Actually, the classical eddy current losses can become too important at high frequencies, while laminated materials only allow flux circulation in the lamination plane, and therefore are not suitable for claw pole machines with 3D flux paths [2]. Soft Magnetic Composites can be a satisfying solution, because their granular structure brings about a significant reduction of the classical losses [3], while exhibiting good isotropic properties [4]. Consequently, there is a clear necessity to provide machine designers loss results and models for such materials under multi-dimensional induction excitations.

The relatively low susceptibility of SMC, and the necessity to reach the range of frequencies for which these materials are designed, can make the experiments particularly difficult. For laminations, most of the 2D induction loss results are provided for the industrial frequency of 50 Hz [5], or up to 200 Hz [6]. On the contrary, SMC require testing in the kilohertz range [4]. A few papers present such results. In [4], the peak induction of 0.54 T has been reached for a maximum frequency of 1000 Hz under 3D induction loci, using a special winding of the measurement setup (the number of turns is decreased while the frequency increases). In [7] loss results under alternating and circular inductions in a SMC disk sample up to 1.25 T at 1000 Hz are proposed, using a specially designed three phase magnetizer. However, contrary to the alternating induction case [8], no comparative study of the loss under multi-dimensional induction waveforms in different SMC samples (with different grain sizes, different preparation methods or binder…) has been performed so far. This makes difficult the choice

of the best SMC for a given application.

In this paper, three different SMC samples have been experimentally characterized under alternating and circular induction loci up to the kilohertz range, using the system presented in [7]. In the following we discuss first experiments made up to peak polarization J_p = 1.25 T. It is shown that, in spite of different loss values and behaviors in the different materials, the ratio of the circular to the alternating hysteresis loss components appears to be quite independent of the sample, the same being also true for the excess loss. We consider then the material behavior at higher peak polarizations, experimentally showing that the J_p value at which the hysteresis loss under circular polarization reaches its maximum is correlated with the material susceptibility.

II. EXPERIMENTAL

A. Measurement setup

The measurement setup for SMC testing under 2D induction is similar to the one used in [7]. Disk-shaped samples have been pressed directly to the final size (diameter 80 mm, thickness 3 mm), i.e. no cutting has been made. For mechanical reasons, samples thinner than 3 mm could not be manufactured. The disk samples have been centered in the bore of a three phases/two poles magnetizer endowed, for maximum field homogeneity, with three slots per pole and per phase and a toroidal winding, minimizing the copper losses and avoiding overhangs crossing. The geometry of the magnetizer has been optimized by 3D finite elements, in order to reach the best induction-frequency combination under power supply by a CROWN AUDIO 5000VZ linear amplifier.

The loss measurements were performed out by the fieldmetric method (double B-coil and H-coil [7]). The measurement zone is a square of 20 mm at the center of the sample, offering a good compromise between signal strength and induction homogeneity, the latter being verified by a finite element computation, as made in [9]). The H-coils have been tested by an impedance analyzer to check that the capacitive effects between turns were negligible in the measurement range of frequencies.

Induction loci are controlled thanks to a feedback algorithm [10]. For the case of alternating sinusoidal induction, the loss measurements have been carried out along two perpendicular directions and the results have been averaged. For measurements under circular polarization, averaging is made of the loss figures obtained for clockwise and counterclockwise rotation.

B. Investigated SMC materials

In this paper, three kinds of commercial SMC are characterized and compared. These materials are made of pure iron grains with electrical conductivity $\sigma_{Fe}=9.93\cdot10^6$ S/m (detailed information is given in Table I). The first two materials have been obtained using inorganic binders and are heat-treated at much higher temperature than Material 3, where an organic binder is used. The compacting pressure is also higher for the first two materials. The micrographic inspection shows that Material 1 has much larger average grain size than Materials 2 and 3 (167 µm versus 46 µm and 57 µm, respectively). Material 3 shows quite larger dispersion of the grain size than Materials 1 and 2. The higher magnetic susceptibility of Material 1 makes it suitable for applications in electrical machines. Materials 2 and 3, with smaller grain size and higher resistivity (because of their lower density, the grain-to-grain contacts are reduced), have lower classical eddy current losses. They are consequently more suitable for high-frequency applications, such as power electronics inductors or very high speed machines [11].

III. ROTATIONAL AND ALTERNATING LOSSES UP TO J_P = 1.25 T

In this Section, energy losses measured under circular and alternating sinusoidal induction are provided up to a few kHz for low and medium induction levels and maximum peak polarization J_p = 1.25 T. Using a classical loss model, it is possible to separate the loss components and analyze for each material the ratios between hysteresis loss under circular and alternating conditions $R_{hyst}(J_p)=W_{hyst}^{(CIRC)}(J_p)/W_{hyst}^{(ALT)}(J_p)$, and the excess loss ratios $R_{exc}(J_p)=W_{exc}^{(CIRC)}(J_p,f)/W_{exc}^{(ALT)}(J_p,f)$.

A. Measurements

For each material, loss measurements at the polarization levels J_p = 0.2 T, 0.5 T, 1 T, and 1.25 T have been carried out under circular and alternating sinusoidal induction loci. The results are shown in Fig. 1 for J_p = 0.5 T, 1 T, and 1.25 T. Material 1 has the highest dynamic loss (both under circular and alternating polarization). This is chiefly due to its large grain size, which is responsible for a significant mesoscopic classical loss [8]. The small grain-sized Materials 2 and 3, present in fact quite reduced dynamic loss. This has, however, a counterpart in a higher hysteresis (quasi-static) loss. It is remarked that these behaviors, typically observed under alternating field, equally hold for circular polarization. In the following Section we will more precisely show that the ratios of rotational to alternating loss components (hysteresis, excess, and classical loss) are to a good extend independent of the material.

The effect of the heat treatment is apparent on comparing Materials 2 and 3. Although Material 2 has smaller grain size and is manufactured with a higher compaction pressure (Table 1), it has lower hysteresis loss under identical excitation conditions. Material 2 is prepared with inorganic binder and is heat-treated beyond 500°C, while Material 3, with its organic binder, is cured at low temperatures (200°C), to avoid binder deterioration. Higher hysteresis loss are inevitably associated with Material 3, because, as explained in [12], the heat treatment helps relieving the residual stresses arising during the compaction process.

B. Loss separation under alternating and circular polarization

The starting point of the loss separation is the classical loss computation. The main assumption is, like in [8], that the classical loss remains confined at the scale of the single grain (we speak of microscopic classical loss), and that eddy currents circulating on a larger scale because of random grain-to-grain contacts are negligible. This is a reasonable assumption when considering, as in the present case a few millimeter thick samples [8]. The classical loss computation under alternating field conditions $W_{class}^{(ALT)}(J_p,f)$ is carried out using the microscopic eddy current loss computation proposed

in [13], taking into account the grain size and shape dispersion observed on micrographs. Following [6], the classical loss under circular field conditions is obtained doubling the classical alternating loss, so that the ratio $R_{class} = W_{class}^{(CIRC)}(J_p, f) / W_{class}^{(ALT)}(J_p, f) = 2$.

The ratios of the circular to the alternating hysteresis loss $R_{hyst}(J_p)$ (this loss component being obtained by extrapolating the total loss to zero frequency [7]) are given versus J_p in Fig. 2 for each material. $R_{hyst}(J_p)$ decreases with J_p [7], with the quite interesting property of being little dependent on the material type. This quite in agreement with previous results obtained in Fe-Si laminations having different grain size [14].

A similar comparison for the excess loss ratio $R_{exc}(J_p)$ has been carried out (Fig. 3). It has been experimentally shown in [7] that this ratio is almost frequency independent. A somewhat similar conclusion can be drawn for Materials 1 and 3 (Fig. 3), although the results obtained in Material 3 are very noisy because of the small amount of dynamic loss. Material 2 has so small dynamic loss that an accurate evaluation of the dynamic loss component is not possible.

IV. HYSTERESIS LOSSES UP TO 1.6 T

In this section, higher peak polarization values, up to J_p=1.6 T, are considered, both under circular and alternating flux, for the three materials. The actual measuring frequency f = 50 Hz can be considered as quasi-static in these materials, given the correspondingly negligible dynamic loss contribution. Thus, we can assume $W_{tot}(J_p,50\ Hz) = W_{hyst}(J_p)$.

Quite remarkably, it is observed that the rotational hysteresis loss $W_{hyst}^{(CIRC)}(J_p)$ attains its maximum at different J_p values in the different materials. In particular, $J_{p,MAX}$ drifts from 1.5 T to 1.25 T on going from Material 1 to Material 3. A similar trend cannot be observed in the conventional nonoriented Fe-Si laminations, where $W_{hyst}^{(CIRC)}(J_p)$ invariably attains a maximum value close to J_p = 1.5 T [14]. The fact that $W_{hyst}^{(CIRC)}$ passes through a maximum value, to eventually drop to zero value on the approach to saturation, points to the contribution of the coherent magnetization rotations, which are reversible in

nature, becoming significant with respect to the domain wall processes. It is apparent that the evolution of $W_{hyst}^{(CIRC)}(J_p)$ shown in Fig. 4 is a peculiar consequence of the granular structure of the SMC materials and the role of the internal demagnetizing fields. We actually see in Table I that the drift of the maximum of $W_{hyst}^{(CIRC)}(J_p)$ correlates with a similar drift of the material susceptibility, in turn strictly depending on the material density. It is clear, looking also at the shape of the hysteresis loops, that the susceptibility is chiefly determined by the internal demagnetizing fields, which are pretty strong, in view of the non-negligible thickness of the non-magnetic grain boundary layer. Lower susceptibility SMC are associated with thicker layers, higher average internal demagnetizing effects, and broader distribution of the local demagnetizing coefficients. Very broad distribution of the internal demagnetizing fields implies that higher applied fields are required for achieving any given J_p. It happens then that the domain wall processes are quite not exhausted, contrary to magnetic laminations, when the applied field is high enough to engender coherent rotations in the softer (i.e. surrounded by thinner layers) grains. The coherent rotations tend eventually to occur at lower inductions in the lower susceptibility SMC materials, bringing with them a similar trend for the turning point of $W_{hyst}^{(CIRC)}(J_p)$.

V. CONCLUSION AND PERSPECTIVES

In this paper, measurements under alternating and circular inductions in different SMC types (grain size, binder, preparation) have been proposed, up to 3 kHz. The loss components have been separated, and it has been shown that the ratios of these components, measured under circular and alternating polarization, do not significantly depend on the material type.

The alternating and rotational hysteresis losses have also been measured up to high inductions (J_p = 1.6 T). It has been shown that the rotational hysteresis loss $W_{hyst}^{(CIRC)}(J_p)$ passes through its maximum value at lower J_p values in lower susceptibility materials. This effect, never observed in the conventional soft magnetic laminations, can be qualitatively justified by taking into account that the susceptibility in SMC is chiefly determined by the thickness of the non-magnetic grain boundaries, that

is, the strength of the internal demagnetizing fields. The higher these fields, as occurring in lower density materials, the broader their distribution and the stronger the field to be applied to reach a given J_p value. This inevitably leads to earlier appearance of coherent magnetization rotations with respect to denser materials and anticipated fall of $W_{hyst}^{(CIRC)}(J_p)$ versus J_p.

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Table captions

Table 1: Main physical properties of the SMC materials used in this work.

Figures captions

Fig. 1: Total energy loss per cycle under circular and alternating sinusoidal induction loci as a function of the frequency f, for the induction peak values J_p=0.5 T, 1 T, and 1.25 T.

Fig. 2: Hysteresis loss ratio $R_{hyst}(J_p)=W_{hyst}^{(circ)}(J_p)/W_{hyst}^{(alt)}(J_p)$ versus the peak polarization J_p, for each material.

Fig. 3: Excess loss ratio $R_{exc}(J_p)=W_{exc}^{(circ)}(J_p,f)/W_{exc}^{(alt)}(J_p,f)$ versus the peak polarization J_p, for each material, at three different frequencies (f=100 Hz, 500 Hz, and 1000 Hz).

Fig. 4: Measured loss $W_{tot}(J_p,f$=50Hz) under circular and alternating sinusoidal induction loci, in function of the peak value J_p.

195 **Tables**

Material	Density (kg/m^3)	Compacting pressure (MPa)	Binder	Heat treatment		Mean grain size (µm)	Electrical resistivity (µΩm)	χ_r [b]
				Temp. (°C)	Time (minutes)			
1	7450	800	Inorganic	530	30	167 (rsd[c]=1.1%)	700	440
2	7260	800	Inorganic	530	30	46 (rsd=1.2%)	7000	200
3	7110	600	Organic	200	30	57 (rsd=1.8%)	900	140

196 Table 1

[b] Measured relative magnetic susceptibility, defined for an alternating field as $\chi_r=J_p/(\mu_0 H_p)$, J_p is the peak polarization chosen equal to 1 T, H_p is the corresponding peak magnetic field under static conditions.
[c] The abbreviation rsd means "relative standard deviation", which is, in statistics, the ratio between the standard deviation and the mean of a set of data.

Figures

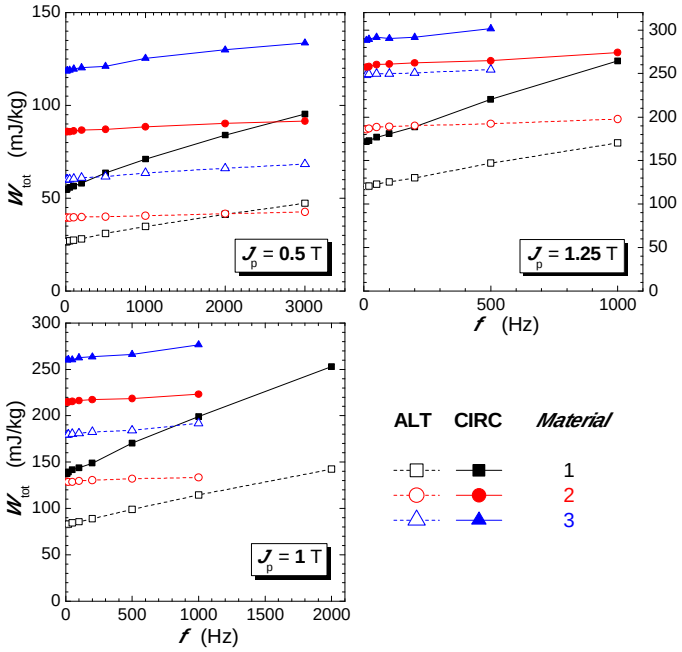
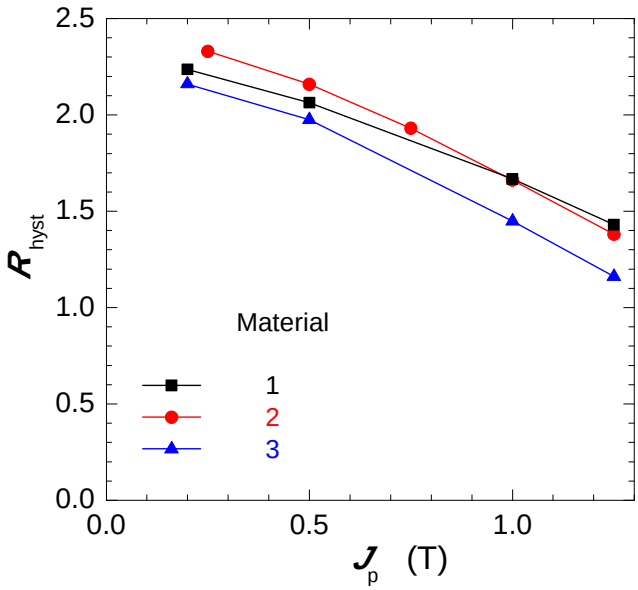


Fig. 1



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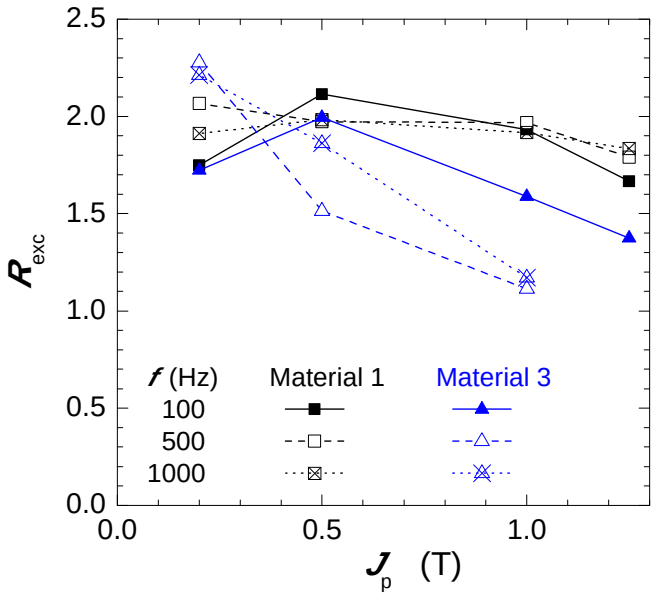
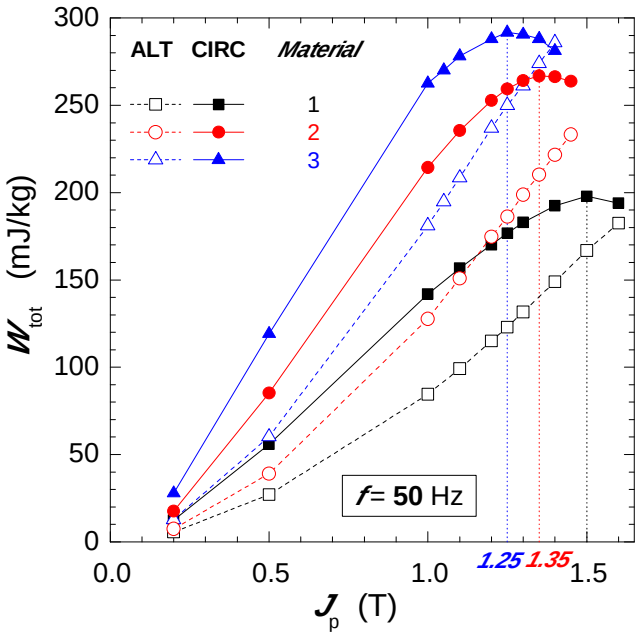
201 Fig. 2


2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
R_{exc}
J_p (T)
f (Hz)
100
500
1000
Material 1
Material 3

202

203 Fig. 3


ALT CIRC Material
1
2
3
f = 50 Hz
1.25
1.35
W_tot (mJ/kg)
J_p (T)
0
50
100
150
200
250
300
0.0
0.5
1.0
1.5

204

205 Fig. 4