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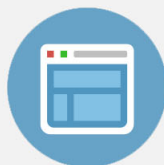
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High-frequency rotational losses in different soft magnetic composites

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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. 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. On the contrary, at higher inductions, it is observed 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. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4865974>]

I. INTRODUCTION

The optimal design of embedded applications involves non conventional electrical machines, such as claw pole generators.¹ In such machines topologies, 3D flux paths are ubiquitous. Therefore, conventional laminated materials, in which the flux can only flow in the lamination plane, may not be suitable anymore. Soft Magnetic Composites (SMC) can be a satisfying solution, because they exhibit good isotropic properties.² 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,³ or up to 200 Hz.⁴ On the contrary, SMC require testing in the kilohertz range.² A few papers present such results,^{2,5} and in any case 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 Ref. 5. 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

Disk-shaped samples (diameter 80 mm, thickness 3 mm) are put in the center of a three phase magnetizer specially optimized by 3D finite elements for reaching frequencies in the kilohertz range.⁵ Measurements are performed exploiting the fieldmetric method,⁴ and a numerical feedback algorithm⁶ allows one to impose both alternating and circular induction loci.

Three kinds of commercial SMC (made of pure iron grains with conductivity $9.93 \cdot 10^6$ S/m) are characterized and compared (all important physical information listed in Table I). 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), present a reduced classical loss component, making them suitable for higher frequency applications, such as power electronics.

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 $R_{\text{hyst}}(J_p) = W_{\text{hyst}}^{(\text{CIRC})}(J_p) / W_{\text{hyst}}^{(\text{ALT})}(J_p)$, and the excess loss ratios $R_{\text{exc}}(J_p) = W_{\text{exc}}^{(\text{CIRC})}(J_p, f) / W_{\text{exc}}^{(\text{ALT})}(J_p, f)$.

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TABLE I. Main physical properties of the SMC materials used in this work.

Material	Density (kg/m ³)	Compacting pressure (MPa)	Binder	Heat treatment		Mean grain size (μm)	Electrical resistivity (μΩ m)	χ_r^a
				Temperature (°C)	Time (min)			
1	7450	800	Inorganic	530	30	167 (rsd ^b = 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

^aMeasured 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 and H_p is the corresponding peak magnetic field under static conditions.

^bThe abbreviation rsd means “relative standard deviation,” which is, in statistics, the ratio between the standard deviation and the mean of a set of data.

For each material, loss measurements at the polarization levels $J_p = 0.2$ T, 0.5 T, 1 T, and 1.25 T (the last three shown in Fig. 1) have been carried out under circular and alternating sinusoidal induction loci. 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.⁷ 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.

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 I), 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 Ref. 8, the heat treatment helps relieving the residual stresses arising during the compaction process.

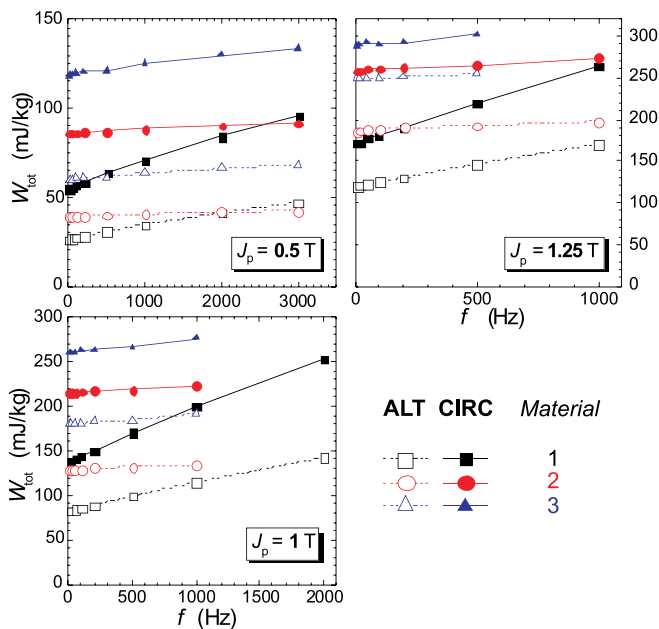


FIG. 1. Total energy loss per cycle under circular and alternating sinusoidal induction loci as a function of the frequency f , for the induction peak values $J_p = 0.5$ T, 1 T, and 1.25 T.

The main assumption is, like in Ref. 7, 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.⁷ The classical loss computation under alternating field conditions $W_{\text{class}}^{(\text{ALT})}(J_p, f)$ is carried out using the microscopic eddy current loss computation proposed in Ref. 9, taking into account the grain size and shape dispersion observed on micrographs. Following Ref. 4 the classical loss under circular field conditions is obtained doubling the classical alternating loss, so that the ratio $R_{\text{class}} = W_{\text{class}}^{(\text{CIRC})}(J_p, f) / W_{\text{class}}^{(\text{ALT})}(J_p, f) = 2$.

The ratios of the circular to the alternating hysteresis loss $R_{\text{hyst}}(J_p)$ (this loss component being obtained by extrapolating the total loss to zero frequency⁵) are given versus J_p in Fig. 2 for each material. $R_{\text{hyst}}(J_p)$ decreases with J_p ,⁵ with the quite interesting property of being little dependent on the material type. This is quite in agreement with previous results obtained in Fe-Si laminations having different grain size.¹⁰ Considering the excess loss ratio, we have pointed out a quite frequency independence of the R_{exc} versus J_p relationship (like in Ref. 5) for all the tested materials. Furthermore, it can be noticed that $R_{\text{exc}}(J_p)$ function weakly depends on the material type.

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 $W_{\text{tot}}(J_p, 50 \text{ Hz}) = W_{\text{hyst}}(J_p)$.

Quite remarkably, it is observed that the rotational hysteresis loss $W_{\text{hyst}}^{(\text{CIRC})}(J_p)$ attains its maximum at different J_p values in the different materials. In particular, $J_{p,\text{MAX}}$ 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 non-oriented Fe-Si laminations, where $W_{\text{hyst}}^{(\text{CIRC})}(J_p)$ invariably attains a maximum value close to $J_p = 1.5$ T.¹⁰ The fact that $W_{\text{hyst}}^{(\text{CIRC})}$ 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

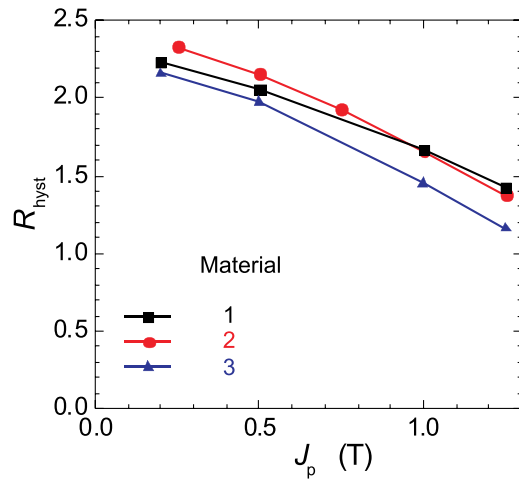


FIG. 2. Hysteresis loss ratio $R_{\text{hyst}}(J_p) = W_{\text{hyst}}^{(\text{circ})}(J_p)/W_{\text{hyst}}^{(\text{alt})}(J_p)$ versus the peak polarization J_p , for each material.

$W_{\text{hyst}}^{(\text{CIRC})}(J_p)$ shown in Fig. 3 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 $W_{\text{hyst}}^{(\text{CIRC})}(J_p)$ 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 $W_{\text{hyst}}^{(\text{CIRC})}(J_p)$.

V. CONCLUSION AND PERSPECTIVES

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 up to $J_p = 1.25$ T.

It has been shown that the rotational hysteresis loss $W_{\text{hyst}}^{(\text{CIRC})}(J_p)$ passes through its maximum value at lower J_p values in lower susceptibility materials. This effect, never

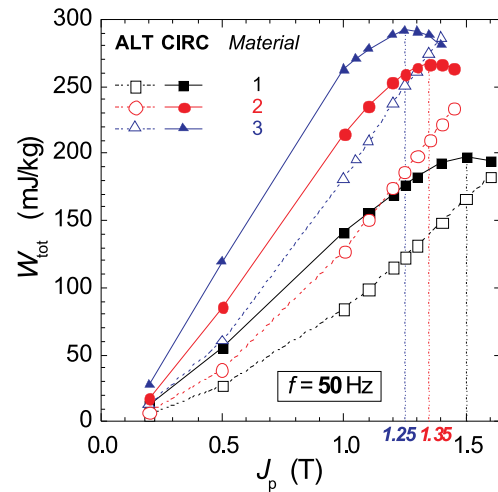


FIG. 3. Measured loss $W_{\text{tot}}(J_p, f = 50 \text{ Hz})$ under circular and alternating sinusoidal induction loci, in function of the peak value J_p .

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 $W_{\text{hyst}}^{(\text{CIRC})}(J_p)$ versus J_p .

¹Y. Guo, J. G. Zhu, Z. W. Lin, H. Lu, X. Wang, and J. Chen, *J. Appl. Phys.* **103**(7), 07F118 (2008).

²Y. Li, J. Zhu, Q. Yang, Z. W. Lin, Y. Guo, and Y. Wang, *IEEE Trans. Magn.* **46**(6), 1971–1974 (2010).

³M. Enokizono, T. Suzuki, J. Sievert, and J. Xu, *IEEE Trans. Magn.* **26**(5), 2562–2564 (1990).

⁴C. Appino, F. Fiorillo, and C. Ragusa, *J. Appl. Phys.* **105**(7), 07E718 (2009).

⁵O. de la Barrière, C. Appino, F. Fiorillo, C. Ragusa, M. Lecrivain, L. Rocchino, H. B. Ahmed, M. Gabsi, F. Mazaleyrat, and M. LoBue, *J. Appl. Phys.* **111**(7), 07E325 (2012).

⁶C. Ragusa and F. Fiorillo, *J. Magn. Magn. Mater.* **304**(2), e568–e570 (2006).

⁷O. de la Barrière, C. Appino, F. Fiorillo, C. Ragusa, H. B. Ahmed, M. Gabsi, F. Mazaleyrat, and M. LoBue, *J. Appl. Phys.* **109**(7), 07A317 (2011).

⁸H. Shokrollahi and K. Janghorban, *J. Mater. Process. Technol.* **187**(1), 1–12 (2007).

⁹O. de la Barrière, C. Appino, F. Fiorillo, C. Ragusa, M. Lecrivain, L. Rocchino, H. B. Ahmed, M. Gabsi, F. Mazaleyrat, and M. LoBue, *IEEE Trans. Magn.* **49**(4), 1318–1326 (2013).

¹⁰C. Ragusa, C. Appino, and F. Fiorillo, “Comprehensive investigation of alternating and rotational losses in non-oriented steel sheets,” *Przegl. Elektrotech.* **85**, 7–10 (2009).