Rotational loss separation in grain-oriented Fe–Si

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Rotational and alternating magnetic losses have been investigated in high permeability grain-oriented laminations as a function of frequency (2.5 Hz ≤ f ≤ 150 Hz) and peak magnetization (0.15 T ≤ I_p ≤ 1.7 T). The results have been analyzed according to the concept of loss separation. The rotational hysteresis W_h and excess W_exc energy loss components exhibit a similar increasing behavior with the magnetization I_p and reach a maximum value around 1.5–1.6 T. W_h shows, in particular, a definite f^{1/2} dependence. The ratios between rotational and alternating hysteresis and excess losses (R_h = W_h/W_{alt}, R_exc = W_{exc}/W_{alt}) follow similar trends with I_p, with their values depending, however, on the testing configuration adopted for the alternating loss measurements (single strip versus X-stacked strips). The 90° domain wall transitions between the in-plane [001] and the out-of-plane [100] and [010] directions are the basic loss producing mechanism under rotational fields, but, on approaching the saturation, the magnetization can eventually rotate only through coherent spin rotations and the classical loss term W_{cl} alone survives. © 2000 American Institute of Physics. [S0021-8979(99)76808-3]

I. INTRODUCTION

Grain-oriented (GO) Fe–Si laminations are used in transformers for their outstanding properties along the rolling direction (RD), but in actual cores they are inevitably subjected to complex fields, imposing flux lines making an angle to RD and 2D fluxes.1 This is the source of relevant problems when modeling the material behavior in electrical devices.2 Additional experimental information is therefore required, which is not easily achieved, because of difficulties and ambiguities in the testing methods.3–4 Somewhat artificial systems have tensorial been proposed in the literature in order to extract the J(H) relationship at any angle θ to RD.3,5 The 2D characterization of the GO laminations, especially focused on the rotational losses, has recently taken advantage of improved electronics and digital methods in the control of the flux loci and data acquisition. However, emphasis on the technical problems related to the measurement accuracy has so far prevailed over the investigation on the physical aspects of the magnetization process.6

In the present study, energy losses under controlled circular magnetization have been determined as a function of frequency f and peak magnetization I_p in high permeability GO laminations. A comparison with the alternating losses, again obtained versus f, has been carried out, exploiting loss separation.7 To this end, strips cut at different angles θ to RD have been tested, distinguishing between two extreme cases, where the demagnetizing fields at the strip edges are large (single strip testing) or negligible (X-stacked strips). It is found that both the rotational hysteresis (i.e., quasistatic) W_h and excess W_exc energy losses attain maximum values about 1.5 T and that W_{exc} f^{1/2}. W_h and W_exc are in a definite relationship with the corresponding alternating quantities, depending, besides θ and I_p, on whether they have been determined under single strip or X-stack configurations. This is understood in terms of relative proportions of 180° and 90° domain wall (dw) processes, the latter being predominant under rotating field and becoming increasingly important with increasing θ under alternating fields.

II. EXPERIMENTAL SETUP AND PROCEDURE

High permeability GO 0.29-mm-thick laminations have been investigated by means of a rotational loss tester, which permits one to achieve circular flux loci up to high inductions (1.7 T in the present measurements) exploiting a 2D digital feedback routine.8 In the present experiments, the sample was placed in a vacuum bell, which was inserted between the pole faces of two orthogonal C-shaped yokes. The sample was made by superposing 4–6 disks of scaling diameters (Φ_{max} = 90 mm), emulating an ellipsoid. The induction derivatives pertaining to the two reference directions y (RD) and x (TD) were detected by means of a couple of orthogonal five-turn windings, obtained by threading the wire through 0.7 mm diameter holes symmetrically drilled on the inner disks at a distance of 32 mm. The derivative of the effective field at the laminations surface was measured by means of two flat many-turn windings, orthogonally arranged on a same thin square former (30 mm×30 mm×0.6 mm). As a rule, the form factor of the x and y induction derivatives was kept within 1.11%±1%. The test frequencies ranged between 2.5 and 150 Hz and the hysteresis loss component W_h was determined, as usual, by extrapolating...
the results to $f=0$, according to the loss separation procedure.\textsuperscript{8} Up to $I_p=1.0\,\text{T}$, the loss calculation was carried out by measuring and summing up the areas of the $I_s(H_y)$ and $I_p(H_y)$ hysteresis loops. At higher inductions, measuring the rate-of-rise of temperature proved more accurate in the determination of the power loss.\textsuperscript{8} Application of both measuring methods at $I_p=1.0\,\text{T}$ showed good agreement of the respectively found loss figures and an overall accuracy around $\pm\,3\%$. The measurements under alternating fields were made on 300 mm long, 120 mm wide strips, cut at angles $\theta$ ranging between 0° and 90° at 15° intervals. Again, a calibrated hysteresisgraph wattmeter with digital control of the induction wave form was employed. The samples, were placed between the pole faces (area 120 mm$\times$30 mm) of a double C-shaped vertical yoke, either as single strips or as two cross-stacked strips. In the first case, substantial macroscopic alignment of $\mathbf{I}$ and the applied field $\mathbf{H}$ is imposed, by the demagnetizing field arising at the strip edges. Complete flux closure at the sample edges is instead achieved by X-stacking and the direction of $\mathbf{I}$ evolves with $\mathbf{H}$ first through [001] directed 180° domain wall displacements, then by 90° transitions from the [001] axes to the [100] and [010] ones.

III. RESULTS AND DISCUSSION

A broad scenario of the rotational loss properties of the high permeability GO alloys has been achieved in this work, by carrying out the loss measurements upon a wide induction range ($0.15\,\text{T} \leq I_p \leq 1.7\,\text{T}$). Representative samples of the obtained results are given in Figs. 1 and 2. The total energy loss $W_{\text{rot}}$ and its separation in the hysteresis, classical and excess loss components ($W_{\text{rot}} = W_{\text{rot}}^c + W_{\text{rot}}^e + W_{\text{exc}}$) is shown in Fig. 1 for two $I_p$ values. One basic result conveyed by these curves is that the rotational losses, like the alternating ones, increase less than linearly with the frequency. In particular, the excess loss component follows to a good approximation a law of the type $W_{\text{exc}} \propto f^{1/2}$, in analogy with the behavior of the same quantity in non-oriented alloys.\textsuperscript{8,10} This kind of dependence, is interpreted as due to the magnetization process becoming increasingly homogeneous with $f$, according to a well defined balance equation involving the applied field and the eddy current counterfields.\textsuperscript{9} It therefore appears that similar eddy current homogenizing mechanisms operate under alternating and rotational fields. The hysteresis and the excess losses are associated with localized eddy current phenomena, tightly connected with the specific displacement mechanisms of the dws. Thus, on approaching the magnetic saturation, $W_{\text{rot}}^c$ and $W_{\text{exc}}$ are bound to decrease, because the dws progressively disappear and the magnetization increasingly rotates in a coherent fashion. It is observed in Fig. 2 that this effect comes into play for a fractional magnetization value $I_p/H_s=0.7–0.8$, where both $W_{\text{rot}}^c$ and $W_{\text{exc}}$ pass through a maximum value. This is consistent with standard literature data.\textsuperscript{11} At saturation, only coherent rotations can occur and the energy loss per unit volume reduces, for a lamination of conductivity $\sigma$ and thickness $d$, to the classical component $W_{\text{rot}}^c = (2\pi^2/3) \times \sigma d^2 I_p f$. The dw processes providing the rotation of the magnetization are both the displacements of the 180° dw's, oriented along the crystal axis [001], and the 90° transitions of the magnetization from [001] to the directions [100] and [010]. The latter processes, responsible for most of the energy dissipation during a cycle, are expected to occur through mechanisms similar to the ones observed when magnetizing a (110) [001] Fe–Si crystal plate along the transverse direction [110].\textsuperscript{12} Here the 90° transitions are revealed, starting from a stable demagnetized state made of bar-like 180° domains directed along [001] and [010], by the progressive formation of sawtooth and columnar surface flux closing domain patterns. Such surface patterns have been shown to cyclically form in Fe–Si single crystals subjected to a rotating field.\textsuperscript{13} The basic difference with the alternating case is that there is no passage through a demagnetized state and the related system of equispaced
180° dws. Figure 3 illustrates the dependence on $I_p$ of the experimental ratios between the hysteresis, excess and total rotational losses and the corresponding alternating quantities determined in the 90° cut laminations. Such ratios ($R_h = W_{rot} / W_{alt}$, $R_{exc} = W_{rot} / W_{alt}$, $R_t = W_{rot} / W_{alt}$) assume, as expected, values around 1, but show a definite increase with $I_p$, a trend opposite to the one observed in nonoriented alloys. Remarkably, at the lowest inductions $R_h < 1$, indicating a more efficient 90° transition process under rotational fields. It is also observed that $R_{exc} < 1$ up to high inductions. On approaching the saturation, $R_h$ and $R_{exc}$ inevitably tend to zero, because the dws tend to disappear. It also follows from the previous discussion that the values taken by these ratios and their behavior with $I_p$ for cutting angles $\theta$ different from 90° depend on the extent to which the 90° domain transitions in the 90° cut laminations. Such ratios ($R_h = W_{rot} / W_{alt}$, $R_{exc} = W_{rot} / W_{alt}$, $R_t = W_{rot} / W_{alt}$) assume, as expected, values around 1, but show a definite increase with $I_p$, a trend opposite to the one observed in nonoriented alloys. Remarkably, at the lowest inductions $R_h < 1$, indicating a more efficient 90° transition process under rotational fields. It is also observed that $R_{exc} < 1$ up to high inductions. On approaching the saturation, $R_h$ and $R_{exc}$ inevitably tend to zero, because the dws tend to disappear. It also follows from the previous discussion that the values taken by these ratios and their behavior with $I_p$ for cutting angles $\theta$ different from 90° depend on the extent to which the 90° domain transitions in the 90° cut laminations. Therefore, the highest. It decreases very rapidly with $\theta$, to eventually change their trend above $\theta$ = 45°. This is related to a correspondingly increasing proportion of the 90° transitions in the alternating magnetization process which, however, dramatically depend on the presence of demagnetizing fields at the strip edges. Thus, on passing, for a given cutting angle $\theta$, from the single strip to the X-stacked strips, the free poles are suppressed and the maximum magnetization span $\Delta \mu = 2 \mu_0 \cos \theta$ will be covered by the 180° dw motion. The $R_h$ vs $I_p$ curve is correspondingly modified, as the example reported in Fig. 4, regarding the 45° cutting angle, illustrates.

ACKNOWLEDGMENTS

This research was partly carried out during a scientific stay of the first author (L. R. Dupré) at IEN Galileo Ferraris. L. R. Dupré is a postdoctoral researcher for the Fund of Scientific Research (FWO-Vlaanderen).
