Energy Losses Analysis of Fe-based and CoFe-based Soft Ferromagnetic Wires

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ABSTRACT

The CoFe-based amorphous and Fe-based nanocrystalline alloys possess excellent soft magnetic properties due to their nearly zero-magnetostriction and very low magnetic anisotropy. So they are good candidate materials for power electronics and giant magneto-impedance (GMI) sensor applications. As an indication of their AC performance, energy losses were determined by the measurements of impedance for $\text{Co}_{68.2}\text{Fe}_{4.3}\text{Si}_{12.5}\text{B}_{15}$ amorphous wire and $\text{Fe}_{73.5}\text{Cu}_{1}\text{Nb}_{3}\text{Si}_{13.5}\text{B}_{9}$ nanocrystalline wires with different domain structure. The measurements were carried out at a frequency range of $10^{-2}$ to $10^{4}$ Hz and induction amplitudes of 0.1 to 1.2 T. Although the measured results show good agreement with the scale theory model of energy loss, different origins of energy loss in the investigated samples have been concluded by comparing the experimental data with the Bertotti’s statistical model. The differences of energy loss in these samples could be explained by considering the magnetic structure and circular technical magnetization processes.

INTRODUCTION

As is known to all, that $\text{Co}_{68.2}\text{Fe}_{4.3}\text{Si}_{12.5}\text{B}_{15}$ amorphous and $\text{Fe}_{73.5}\text{Cu}_{1}\text{Nb}_{3}\text{Si}_{13.5}\text{B}_{9}$ nanocrystalline alloys exhibit huge magnetic permeability and very small coercivity due to their nearly zero-magnetostriction and very low magnetic anisotropy. For this reason, they can be usually applied to kinds of AC components (magnetic core, transformer, energy storage and inductive elements, etc) [1,2]. No matter what is actual application, magnetic losses as one of the most essential parameters need to be determined in advance. There are a lot of theoretical models to predict the energy loss in soft magnetic materials. The loss is usually separated into three portions: (1) the static hysteretic loss, $P_{\text{hys}}$, (2) the classic eddy-current loss, $P_{\text{edd}}$ and (3) the excess (anomalous or dynamic) eddy-current loss, $P_{\text{exc}}$. The most attractive models consist of the Steinmetz law described the hysteresis loss [3], the two-domains [4] and multi-domains [5] models described eddy-current loss, the statistical model by Bertotti [6,7], etc. These models shown good correlation with measurements [8,9] but are artificial and empirical approaches due to trying to separate the different...
physical influences of frequency and flux-density variations in the materials rather than explaining the physical mechanism.

From a physical point of view, the losses in conducting ferromagnetic materials are based on Joule heating \[10\]. Hence, energy loss should be considered as total. Recently, Sokalski, Szczygłowski and Najgebauer tried to give a general description of the phenomenon and proposed a new approach based on the scaling theory \[11,12\]. This so-called scaling model was confirmed by a few of experiments \[13,14\]. In this work, we’ll analyze the energy loss of Co\(_{68.2}\)Fe\(_{4.3}\)Si\(_{12.5}\)B\(_{15}\) amorphous and Fe\(_{73.5}\)Cu\(_{1}\)Nb\(_{3}\)Si\(_{13.5}\)B\(_{9}\) nanocrystalline wires by scaling model. The differences of scaling exponents in the studied samples have been discussed by considering the circular technical magnetization.

**EXPERIMENTS**

Amorphous Fe\(_{73.5}\)Cu\(_{1}\)Nb\(_{3}\)Si\(_{13.5}\)B\(_{9}\) and Co\(_{68.2}\)Fe\(_{4.3}\)Si\(_{12.5}\)B\(_{15}\) wires with diameter \(2r_0 = 0.14\) mm were produced by in-rotating-water quenching technique. In order to improve the soft magnetic properties and tailor the magnetic structure, two pieces of samples (15 cm in length) were cut from amorphous Fe\(_{73.5}\)Cu\(_{1}\)Nb\(_{3}\)Si\(_{13.5}\)B\(_{9}\) wire for heat treatment. The samples were annealed by 750 mA (51 A/mm\(^2\)) DC current for 15 s in air without (S1) or under (S2) application of tensile stress 135 MPa, respectively. As for the measurements of circular permeability, the sample was successively surrounded by a search coil (5-cm long) and a magnetizing solenoid (20-cm long). An \(l = 7\) cm long middle segment of the sample was connected in the circuit for AC impedance measurements. The AC current of \(I = 0.1 - 100\) mA (rms) was provided by the output of a lock-in amplifier, which was also used for measuring the in-phase and out-of-phase AC current (through a 1 \(\Omega\) resistor connected in series) and AC voltage across the middle segment of the sample for calculating the impedance \(Z = R + jX = R + j\omega L\). The AC frequency used for the measurements was in range of \(f = 10 - 10^5\) Hz. The complex circular permeability \(\mu = \mu' - j\mu''\) was derived from the measured impedance as in \[15\].

\[
\mu' = \frac{8\pi X}{\omega l} \quad \text{(1a)}
\]

\[
\mu'' = \frac{8\pi (R - R_{DC})}{\omega l} \quad \text{(1b)}
\]

where \(R_{DC}\), the DC resistance, \(l\), the length of the measured segment of the sample. The circular magnetic induction was calculated by \[16\]

\[
B_\varphi = \mu_\varphi H_\varphi \quad \text{(2)}
\]

where \(\mu_\varphi = \sqrt{\mu'^2 + \mu''^2}\) and \(H_\varphi = 3\sqrt{2I/16\pi_0}\).

**RESULTS AND DISCUSSION**

Average energy loss was determined from the measurements by \[17\]

\[
P = \frac{1}{2} \mu'' \omega H_\varphi^2 = \pi f \mu'' H_\varphi^2. \quad \text{(3)}
\]

According to the scaling model, the total energy loss, \(P\), can be expressed as a generalized homogeneous function of frequency, \(f\), and maximum induction, \(B_m\).
\[ P = F(f, B_m), \] 
\[ \forall \lambda > 0, \quad \mathcal{K} P = F(\mathcal{K} f, \mathcal{K} B_m), \]

where \( a, b, c \) are scaling exponents. Consequently, the following formula for energy loss was deduced immediately

\[
P \approx B_m^\beta \left[ \Gamma^{(1)} \frac{f}{B_m^\alpha} + \Gamma^{(2)} \left( \frac{f}{B_m^\alpha} \right)^2 + \Gamma^{(3)} \left( \frac{f}{B_m^\alpha} \right)^3 + \ldots \right],
\]

where \( \alpha, \beta \) are related to exponents of Eq. (5):

\[
\beta = c/b \quad \text{and} \quad \alpha = a/b,
\]

and \( \Gamma^{(n)} (n = 1, 2, 3, \ldots) \) are the arbitrary coefficients. The measured results and scaling model fitting of the studied samples are depicted in Fig. 1 in the coordinate system \( P/B_m^\beta = F(f/B_m^\alpha) \). Values of exponents \( \alpha, \beta \) and amplitudes \( \Gamma^{(n)} (n = 1, 2) \) for three samples are given in Table 1. The linear relationship of exponents \( \alpha \) and \( \beta \) [12] \( \beta = 1.35 \alpha + 1.75 \) is tested for the studied samples (see Fig. 2). On the other hand, the expansion (6) can be cut off above the third order due to very small values of \( \Gamma^{(n)} (n > 2) \) and transformed into the following form [12]

\[
P^* = f^* + f^{*2}
\]

where \( P^* = \frac{\Gamma^{(2)} P}{\Gamma^{(1)} B_m^\beta} \) and \( f^* = \frac{\Gamma^{(2)} f}{\Gamma^{(1)} B_m^\alpha} \)

are scaled energy loss and scaled frequency, respectively. Eq. (8) is sample-independent and can be taken as a universal formula for energy loss in soft magnetic materials. The distribution of measurement points around theoretical curve given by Eq. (8) is plotted in Fig. 3. The data collapse indicates the correction of scaling theory in energy loss of soft magnetic materials.
It’s interesting to compare the different values of $\alpha$ and $\beta$ in order to have a clear understanding of the origins of energy loss in the investigated samples. According to the statistical model, the energy loss can be described by [6]

$$
P = P_{\text{hys}} + P_{\text{edd}} + P_{\text{exc}} = \gamma fB_m + C_1 fB_m^2 + C_2 (fB_m)^{3/2}$$

where $\gamma$, $C_1$, $C_2$, and $C_3$ are constants. The hysteresis loss ($P_{\text{hys}}$) and eddy-current loss ($P_{\text{edd}}$ and $P_{\text{exc}}$) should correspond to the first term and other higher terms of Eq. (6), respectively. Consequently, for the studied samples, we have

$$
P_{\text{hys}} = \Gamma^{(1)} fB_m^{\beta - \alpha}$$

$$
P_{\text{edd}} + P_{\text{exc}} = \Gamma^{(2)} f^2 B_m^{\beta - 2\alpha}$$

TABLE 1. VALUES OF EXPONENTS $\alpha$, $\beta$ AND AMPLITUDES $\Gamma^{(1)} (n = 1, 2)$.

| samples       | $\alpha$ | $\beta$ | $\Gamma^{(1)}$ | $\Gamma^{(2)} (10^{-3})$ | $\beta - \alpha$ | $\beta - 2\alpha$ |
|---------------|----------|---------|----------------|--------------------------|------------------|------------------|
| CoFeSiB       | -0.50    | 1.00    | 8.37           | 3.90                     | 1.50             | 2.00             |
| FeCuNbSiB(S1) | -0.60    | 0.88    | 42.2           | 8.07                     | 1.48             | 2.08             |
| FeCuNbSiB(S2) | 0.50     | 2.45    | 68.4           | 9.65                     | 1.95             | 1.45             |
From the values of $\beta - \alpha$ and $\beta - 2\alpha$ presented in the Table 1, one can see that the energy losses consist roughly of hysteresis loss with $\gamma \approx 1.5$ and classical eddy-current loss for the extremely soft magnetic CoFeSiB amorphous and FeCuNbSiB (S1) nanocrystalline wires. However, for FeCuNbSiB (S2) with a large transverse anisotropic field ($H_k = 3.2$ kA/m), the energy loss originate mainly from hysteresis loss with $\gamma \approx 2$ and excessive eddy-current loss. This is roughly consistent with previous works of low-frequency eddy-current anomaly factors for these samples [18].

The differences of energy loss in the studied samples reveal the complication of this phenomenon as we had analyzed by considering the magnetic structure and
circular technical magnetization processes of the samples [19]. The features of circular magnetization processes in the studied samples are determined by Eq. (2) and displayed in Fig.4. In general, the contribution of domain wall displacement (DWD) to power loss in CoFeSiB amorphous wire with bamboo-like domains and FeCuNbSiB (S1) nanocrystalline wires with helical domains couldn’t be very large because of their huge permeability and tiny coercivity. So the majority of power loss is from the classic eddy-current. Nevertheless, for FeCuNbSiB (S2) nanocrystalline wire with transverse domains structure, DWD due to large Barkhausen jump dominates the circular technical magnetization processes, so the majority of power loss should result from the excess eddy-current.

CONCLUSIONS

Although there are many theoretical models about the energy loss in soft magnetic materials, the scaling theory shows quite good description to this complicated problem. The differences of energy loss in the studied samples have been discussed with the Bertotti’s statistical model by considering the magnetic structure and circular technical magnetization processes.

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