Broadband magnetic losses in soft magnets: experimental and theoretical analysis

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The modern inducting, transforming, and absorbing devices dedicated for operation under increasingly wide range of frequencies call for magnetic cores with good wideband response. Smart nanocrystalline ribbons treated under specific magneto-thermal conditions can exhibit superior broadband magnetic behavior with respect to Mn-Zn ferrites, the materials of traditional industrial choice. Because of the very low ribbon thickness (10 – 20 micrometers), the eddy currents are significantly constrained and low energy dissipation up to very high frequencies is observed in these alloys, in spite of their metallic character. A narrow experimental window of material characterization is generally found in the literature. This limitation has so far precluded a thorough quantitative understanding of the involved microscopic magnetic phenomena and a comprehensive broadband comparison between ferrite and nanocrystalline properties.

In this communication we present an overview of the broadband magnetic permeability and loss behavior of sintered Mn-Zn ferrites and amorphous/nanocrystalline ribbons. To meet the challenging conditions envisaged for applications, we performed extensive fluxmetric measurements from DC regime up to 10 MHz, spanning a wide region of peak polarization J_p values, in combination with transmission line measurements, by which the GHz region could be approached. We report on recent progress made in understanding the complex phenomenology of loss and permeability behavior on such a broad range of frequencies range in all these materials. A comprehensive interpretative framework, relying on the statistical theory of losses and the related loss separation concept [1], has been worked out. It is aimed at the theoretical assessment of the involved magnetization process mechanisms (domain wall displacements and rotations) and the associated dissipation channels (eddy currents and spin damping).

The rotational process in ferrites and the related energy dissipation by spin damping are predicted through the Landau–Lifshitz–Gilbert (LLG) equation for spin dynamics under frequency-evolving distribution of the local anisotropy fields and the ensuing spectrum of resonance frequencies. Eddy-current losses have a classical character and can be predicted by numerical multiscale variational approach [2]. They can any case be experimentally separated from the spin-damping losses, because eddy current-free loss in Mn-Zn ferrites can be obtained in rings of reduced thickness (~ 1 mm).

The best broadband combination of low losses and high permeability is obtained with the amorphous/nanocrystalline ribbons endowed with transverse low-value magnetic anisotropy, as induced by conventional field annealing. These materials provide a highly interesting and analytically treatable case, because their magnetization process is dominated by rotations and the ensuing dynamic losses can correspondingly be calculated by recognizing a frequency-dependent magnetic constitutive equation, obtained as solution of the LLG equation, and applying to it the electromagnetic diffusion equation. Fig. 1 shows the wideband loss separation performed on a Mn-Zn ferrite (Fig. 1a) and a nanocrystalline transverse anisotropy Finemet ribbon (Fig. 1b). The rotational loss contribution $W_{rot,sd}$ due to spin damping in ferrites is predicted using the Landau–Lifshitz constant $\alpha_{LL} = 0.04$, while the classical loss term $W_{rot} = W_{rot,sd} + W_{rot,eddy}$ in transverse anisotropy tapewound ribbon is obtained for $\alpha_{LL} \sim 0.06$ and the exchange stiffness constant $A \sim 2 \times 10^{-11}$ J/m. The excess loss W_{exc}, calculated as $W_{exc}(f) = W(f) - W_{hyst} - W_{rot}(f)$, follows a law $W_{exc}(f) \propto f^{q}$, where $0 < q \leq 1$ [3]. The theoretically predicted dynamic behavior of the domain walls, relaxing beyond a few hundred kHz, is experimentally supported by high-speed magneto-optical *in situ* observations of their domain structure [4].

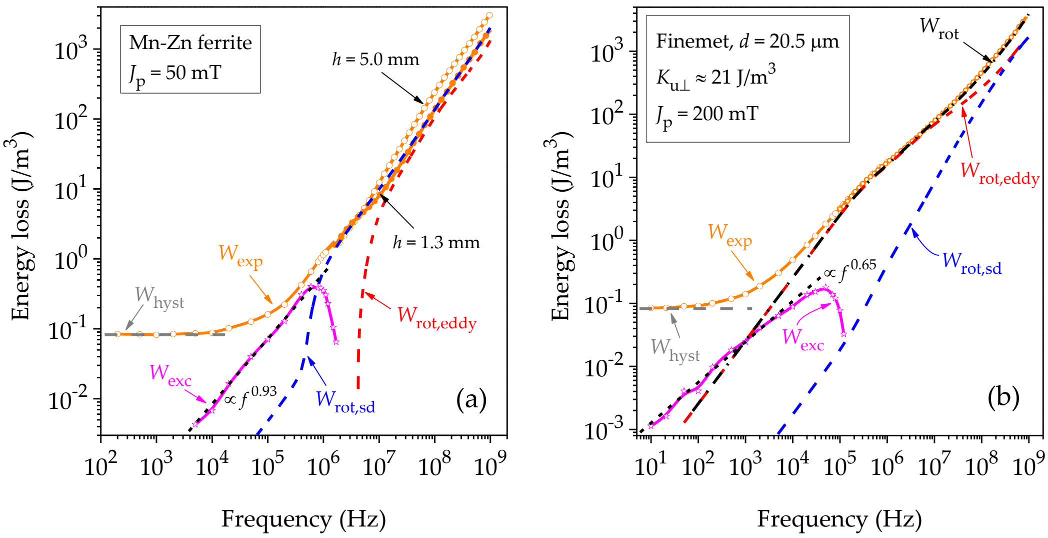

Figure 1: Broadband magnetic losses measured (a) in a Mn-Zn ferrite ring with two different values of thickness h and (b) in a 20.5 μm thick tapewound nanocrystalline transverse anisotropy Finemet ribbon at a defined J_p level. The measured loss $W_{exp}(f)$ is decomposed into the quasi-static hysteresis W_{hyst} component and the dynamic $W_{exc}(f) + W_{rot,eddy}(f) + W_{rot,sd}(f)$ contribution.

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