Journal of Magnetism and Magnetic Materials 420 (2016) 317–323

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Broadband magnetic losses of nanocrystalline ribbons and powder cores

Cinzia Beatrice [a,*], Samuel Dobák [b], Enzo Ferrara [a], Fausto Fiorillo [a], Carlo Ragusa [c], Ján Füzer [b], Peter Kollár [b]

[a] *Istituto Nazionale di Ricerca Metrologica, Nanoscience and Materials Division, Torino, Italy*
[b] *Institute of Physics, Faculty of Science, P.J. Šafárik University, Košice, Slovakia*
[c] *Politecnico di Torino, Energy Department, Torino, Italy*

ARTICLE INFO

Article history:
Received 30 May 2016
Accepted 22 July 2016
Available online 28 July 2016

Keywords:
Nanocrystalline alloys
Magnetic losses
High-frequency losses
Landau–Lifshitz equation

ABSTRACT

Finemet type alloys have been investigated from DC to 1 GHz at different induction levels upon different treatments: as amorphous precursors, as ribbons nanocrystallized with and without an applied saturating field, as consolidated powders. The lowest energy losses at all frequencies and maximum Snoek's product are exhibited by the transversally field-annealed ribbons. This is understood in terms of rotation-dominated magnetization process in the low-anisotropy material. Intergrain eddy currents are responsible for the fast increase of the losses with frequency and for early permeability relaxation of the powder cores. Evidence for resonant phenomena at high frequencies and for the ensuing inadequate role of the static magnetic constitutive equation of the material in solving the magnetization dynamics via the Maxwell's diffusion equation of the electromagnetic field is provided. It is demonstrated that, by taking the Landau–Lifshitz–Gilbert equation as a constitutive relation, the excellent frequency response of the transverse anisotropy ribbons can be described by analytical method.

1. Introduction

Nanocrystalline Finemet-type alloys combine high magnetic softness and versatility with excellent broadband response, comparable or even superior, in terms of permeability and loss behavior, to the one offered by soft ferrites [1–3]. Once reduced in powder form and consolidated as conventional ring samples, they may exhibit nearly flat permeability response up to a few hundred MHz [4,5]. But, while faced with a wide range of applications [6], these materials display a poorly assessed broadband behavior, where the analysis is, as in the case of amorphous alloys, mostly qualitative and generally limited to the description of the frequency dependence of the initial permeability [5,7,8]. Quantitative description and prediction of magnetic permeability and energy loss behavior in metallic alloys up to radiofrequencies are indeed difficult objectives and drastic approximations are usually required. Permeability and impedance of planar magnetic conductors have, for example, been calculated disregarding the role of the domain walls (d.w.s) and assuming linear response by the rotational processes [9,10]. Thanks to these approximations one can actually perform the analysis of eddy currents at microwave frequencies by taking the Landau–Lifshitz–Gilbert (LLG) equation as the constitutive magnetic relation of the material in the description of electromagnetic field diffusion by the Maxwell's equations [11,12]. Wishing, however, to assess the material response both at high and low frequencies, one should additionally take into account the d.w. processes, the sole source of the quasi-static energy loss and responsible for the generation of dynamic loss in excess of the one predictable according to a homogeneous d.w. free magnetization process [13]. This feat has not been accomplished yet.

In this paper we discuss a comprehensive experimental investigation on the DC-1 GHz behavior of permeability and energy losses, measured at defined peak polarization levels ($0.5\ \mathrm{mT} \le J_p \le 200\ \mathrm{mT}$), of the $Fe_{73}Nb_3Cu_1Si_{16}B_7$ (Finemet) nanocrystalline alloy. Both tapewound and consolidated powder ring samples have been measured. Best broadband response is obtained with ribbons nanocrystallized and cooled under a saturating transverse DC magnetic field, a feature associated with a relatively sharp transverse domain structure, leading to prevalence of the rotational magnetization processes. It is shown that the standard analysis based on the statistical theory of losses permits us to apply, in general, the usual concept of loss separation, also in the presence of skin effect, up to some hundred kHz. By keeping, in particular, the induction values sufficiently low, as required in most high-frequency applications, the condition of quasi-linearity

---

* Corresponding author.
E-mail address: c.beatrice@inrim.it (C. Beatrice).

http://dx.doi.org/10.1016/j.jmmm.2016.07.045
0304-8853/

of the DC magnetic constitutive equation is satisfied and a standard equation for the classical loss component applies. Entering, however, the MHz range, where the diffusion of the electromagnetic field interferes on a same time scale with the spin dynamics, a dynamic constitutive relation is expected to emerge and govern the dissipation of the magnetic energy. Such a relation is generally unknown, although one could imagine retrieving it by solution of an inverse problem. We show, however, that the especially interesting case of the low-loss transverse anisotropy ribbons, with their weakly contributing transverse d.w.s, can be treated describing the magnetic constitutive relation through the Landau–Lifshitz equation. Such an approach, substantiated by experimental evidence of magnetic resonance effects, is pursued by an analytical procedure and permits one to provide broadband fitting of the measured energy loss.

2. Experimental procedure and basic results

Tapewound 18 mm diameter ring samples were prepared with 10 mm wide 20 μm thick $Fe_{73}Nb_3Cu_1Si_{16}B_7$ precursor amorphous ribbons, obtained by planar flow casting and encased in boron nitride toroidal holders. No tensile stress was applied to the ribbon during winding, the number of layers varying between 3 and 10 from sample to sample. Nanocrystallization annealing, performed at 550 °C, was followed by slow cooling to room temperature, with and without an applied saturating DC field. Either circumferential ($H_{//}=300$ A/m) or transverse ($H_\perp=15$ kA/m) fields were applied, in order to induce longitudinal/transverse anisotropy. Composite ring samples (outside diameter 10 mm, inside diameter 5 mm, thickness 3.3 mm) were also prepared, as described in [8], by pulverization of the precursor ribbon at either room temperature or liquid nitrogen temperature, powder consolidation, and nanocrystallization annealing. Particles of size 20–150 μm were produced by cryomilling (sample L), smaller on the average with respect to the particles (50–300 μm) obtained by milling at room temperature (sample R). The resistivity values of the composites, approximately doubled with respect to the resistivity of the alloy ($256 \cdot 10^{-8}\ \Omega$ m in sample R and $273 \cdot 10^{-8}\ \Omega$ m in sample L versus $121 \cdot 10^{-8}\ \Omega$ m), point to good interparticle contact and nearly homogeneous bulk conduction. The magnetic characterization of the ring samples was performed by fluxmetric measurements at defined peak polarization level J_p up to 10 MHz. A transmission line (TL) method using a Vector Network Analyzer (Agilent 8753 A) and TEM wave power $P_{TL}=10$ mW on a short circuited coaxial line was instead adopted in the range $100\ \text{kHz} \le f \le 1$ GHz [14]. It is shown that, as far as a quasi-linear response of the material applies, the measured high-frequency real μ′ and imaginary μ″ permeability components are independent of P_{TL} (i.e. J_p) [15] and one obtains the energy loss at a given J_p value as

$$W(J_p, f) = \pi J_p^2 \mu''(f)/(\mu'^2(f) + \mu''^2(f))\left[J/m^3\right]. \tag{1}$$

Fig. 1 provides an example of experimental μ′ and μ″ dependence on frequency in the transverse anisotropy $K_\perp$ ($H_\perp$ annealed) ribbons, where the fluxmetric measurements (symbols), taken up to a few MHz at $J_p=20$ mT, are observed to seamlessly connect to the high-frequency TL results, a property ensuing from the linear response of the material. This finding is corroborated by magneto-optical Kerr experiments, showing that the d.w. processes are progressively inhibited with increasing the frequency towards the MHz range, leaving room for the linear magnetization rotations [16]. It is notably observed in Fig. 1 (see inset) that μ′(f) attains negative values beyond some hundred MHz and the related dispersion behavior points to magnetic resonance phenomena.

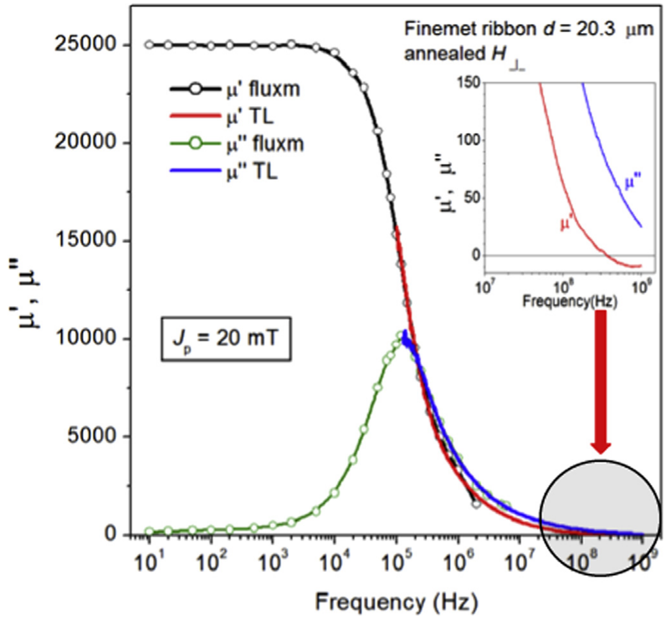

Fig. 1. Real μ′ and imaginary μ″ permeability components versus frequency measured in the transverse anisotropy Finemet ribbon of thickness $d=20.3$ μm. The fluxmetric measurements (symbols) are performed at a defined peak polarization value $J_p=20$ mT up to a few MHz. The transmission line (TL) results (continuous lines), obtained in the upper frequency range with TEM wave power $P_{TL}=10$ mW, coincide with the fluxmetric measurements beyond a few hundred kHz. The passage of μ′ through negative values beyond a few hundred MHz (see inset) points to resonant dispersion associated with the rotational processes.

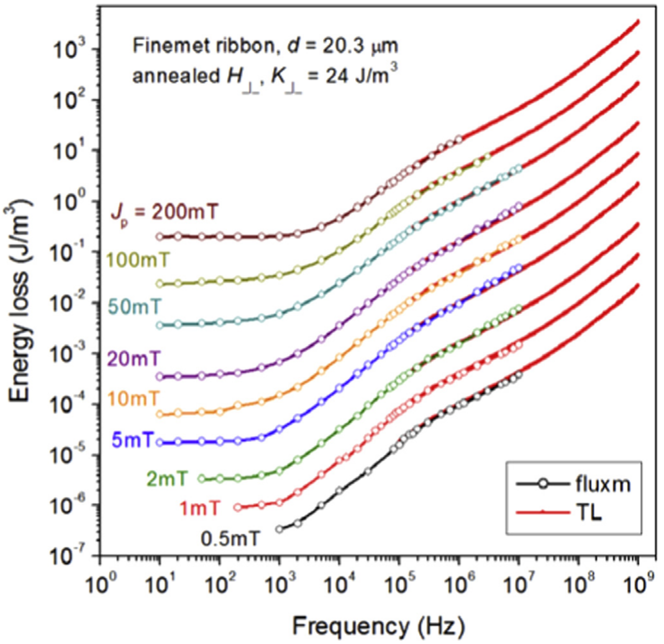

Fig. 2. Energy loss W(f) versus frequency up to $f=1$ GHz in the transverse anisotropy nanocrystalline ribbon. W(f) is directly measured at given peak polarization value J_p by the fluxmetric method up to the maximum frequency $f=10$ MHz (symbols). By the transmission line (TL) method one gets, starting from a few hundred kHz, the real μ′(f) and imaginary μ″(f) permeability components at defined TEM wave power. W(f) is then calculated for any J_p value by Eq. (1) (continuous lines). The two methods provide matching W(f) values in the overlapping frequency interval.

An overall view of the DC – 1 GHz $W(J_p, f)$ behavior of the $K_\perp$ ribbons, with J_p ranging between 0.5 mT and 200 mT, is provided in Fig. 2, where the fluxmetric measurements are shown to smoothly superpose, for all J_p values, to the TL results at intermediate frequencies. It is stressed that by