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Research articles

Soft magnetic materials for sensor applications in the high frequency range

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ABSTRACT

The increase in the number of materials for research and extending the list of their applications requires a parallel optimization of the methods of characterization. Microwave magnetoimpedance (MI) in low magnetic fields was proposed for the characterization of the axial magnetization process in different materials. Characterization of the same parameter using different techniques becomes increasingly required. Here we describe our experience in the comparative analysis of magnetic properties, giant magnetoimpedance, ferromagnetic resonance (FMR), and low field MI of CuBe/$Fe_{19}Co_{17}Ni_{64}$ electroplated and $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ in-water solidified amorphous wires. Microwave studies were conducted using specially designed installation on the basis of Rohde & Schwarz ZVA-67 Vector Network Analyzer for two lengths of the wire of 3 and 6 mm. FMR was also measured using classic cavity perturbation technique. The analysis of the results allows us to observe evolution of the intensity of two absorption peaks and conclude the corresponding to MI and FMR features.

1. Introduction

During the past two decades soft magnetic materials for sensor applications have been the subject of an active research. Although fabrication of soft ferromagnets for sensor applications follows well developed methods there have been advances and improvements in the existing techniques. The increase in the number of materials for research and extending the list of their applications requires a parallel optimization of the methods of characterization. Soft ferromagnetic materials were extensively studied for the following main types: rapidly quenched in water wires [1,2], rapidly quenched ribbons [3], electroplated wires [4], glass covered microwires [5] and thin films [6]. Apart from magneto-inductive behaviour, giant magneto-impedance (GMI) [4,5], ferromagnetic resonance (FMR) [7,8] and low field magnetoimpedance (MI) were also under consideration. In particular, MI in low magnetic fields was proposed for the characterization of the axial magnetization process in different materials [7,8]. Despite the time period of above 15 years of exploration since the new wave of the interest to this phenomenon, the theoretical background is still very limited [9,10]. One of the reasons for slow development of the theories, actually, is a very limited number of studies showing high quality experimental results. Last decade can be described as a shift toward high frequency applications of magnetic materials stimulated by the market request and understanding that complete characterization of particular type of material nowadays requires the employment of the whole set of available techniques for structural and magnetic characterization, the last one from quasistatic to manetodynamics. The dynamic properties are more and more requested for a wide frequency range. To satisfy the last demand different systems were developed recently on the basis of Vector Network Analysers (VNA) [11,12] providing significantly higher quality data sets.

We describe our experience in the comparative analysis of magnetic properties, GMI, FMR and low field MI for $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ in-water solidified amorphous and CuBe/$Fe_{19}Co_{17}Ni_{64}$ electroplated wires. Microwave studies were conducted in installation on the basis of Rohde & Schwarz ZVA-67 VNA.

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2. Experimental methods

$Cu_{98}Be_2$ non-magnetic wire of 100 μm in diameter was prepared by cold drawing. After careful mechanical polishing thin copper layer of about 10 μm and magnetic layer with $Fe_{19}Co_{17}Ni_{64}$ nominal composition were deposited by using a standard electrodeposition technique. A magnetic FeCoNi tube with uniform thickness of 1 μm was formed. More details on the preparation and characterization can be found elsewhere [4]. Fig. 1(a) shows the general view of the CuBe/FeCoNi electroplated wire (EP) obtained through scanning electron microscopy (SEM).

We selected amorphous wire (AW) with $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ composition designed by Unitika Corporation, Japan. Samples for this study were prepared by water quenching method at CSIC, Madrid. Fig. 1(b) shows the general view of the $(Co_{0.94}Fe0.06)_{72.5}Si_{12.5}B_{15}$ in water quenched 150 μm in diameter amorphous wire with small negative magnetostriction. Apart from classic X-ray diffraction technique SEM images were effectively used for amorphous structure confirmation: typical for glassy material deformation near the cut end was evident.

The low frequency hysteresis loops were measured at room temperature either using classic inductive method or the vibrating sample magnetometer (VSM) for the samples of 3–20 mm. Fig. 2(a) shows M(H) loops the EP and (b) AM wires: the length plays an important role in the determination of the magnetization process. The values of the saturation magnetization (M_s) were 880 G for EP and 630 G for AP wires. The GMI measurements were carried out using alternating exciting current flowing parallel to the applied filed. GMI was measured using a precision Agilent HP e4991A impedance analyzer in the “microstripe” line following the standard calibration [13]. The total impedance and its components were studied from 1 to 100 MHz frequency (f) range and 10 mA intensity of sinusoidal exciting current. The GMI ratio for total impedance (ΔZ/Z) was defined as follows:

$$\left(\frac{\Delta Z}{Z}\right)(\%) = \left(\frac{Z(H) - Z(H_{\max})}{Z(H_{\max})}\right) \times 100\% \quad (1)$$

where H_{max} = 100 Oe. The length (l) of the samples for magnetic and GMI measurements was from 3 to 20 mm. Maximum value of ΔZ/Z for fixed frequency was designated as $\Delta Z/Z_{max}$.

The microwave studies of the wires properties were done either by cavity perturbation technique for fixed frequency [7], or using a specially designed installation with the Rohde & Schwarz ZVA-67 VNA as its main element with possibility of application of the magnetic field of −20 to +20 kOe (S_{11} reflection coefficient was measured). All microwave studies were made for the wires of 6 or 3 mm length.

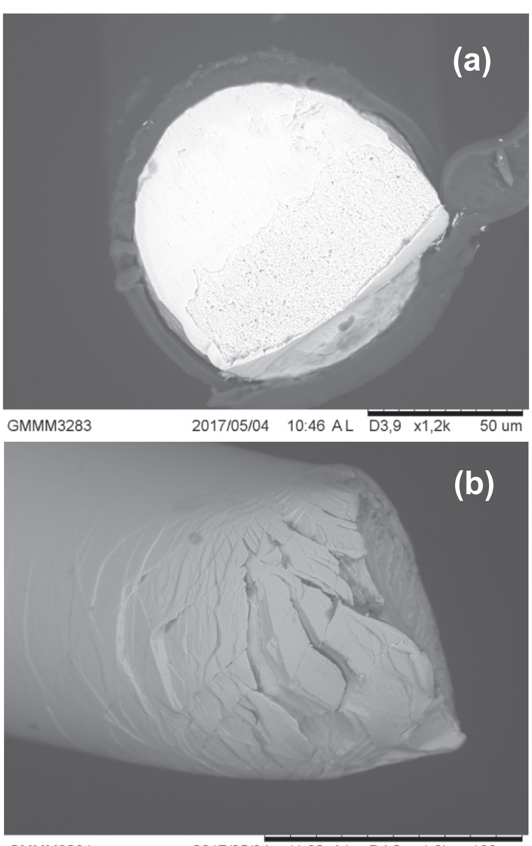

Fig. 1. SEM general view of CuBe/$Fe_{19}Co_{17}Ni_{64}$ EP wire (a) and in water solidified $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ AM wire (b).

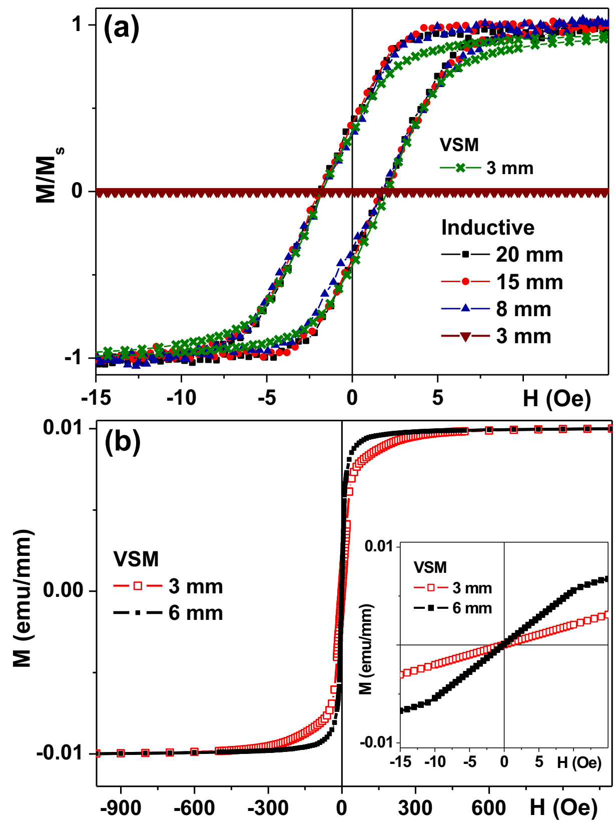

Fig. 2. Quasi-static hysteresis loops of CuBe/$Fe_{19}Co_{17}Ni_{64}$ EP (a) and $(Co_{0.94}Fe0.06)_{72.5}Si_{12.5}B_{15}$ AM wires of different lengths measured in the external field parallel to the wire axis. Inset: M(H) loops of AM wires in low field.

3. Results and discussion

The shape of the M(H) loops of EP wires was consistent with the assumption of the circular effective magnetic anisotropy and circular magnetic domain structure. For 8 and 3 mm long wires slower approach to saturation was evident. The shape of the M(H) loops of AM wires had similar features but the coercivity (H_c) was lower and the field to reach saturation higher in comparison with EP. The circumferential easy magnetization axis in shell part of AM wire was reflected in the M(H) loops shape.

Fig. 3 shows the frequency and field dependences of the GMI. The shapes of the $\Delta Z/Z_{max}(f)$ curves were quite similar for both kinds of wires but much higher values $\Delta Z/Z_{max}$ were observed in