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Effect of domain structure on the impedance of ferromagnetic wire with circumferential anisotropy

Ján Ziman, Viktória Šuhajová, Mária Kladivová*

Department of Physics, Faculty of Electrical Engineering and Informatics, Technical University of Košice, Park Komenského 2, 04200 Košice, Slovakia

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ABSTRACT

Circumferential domain structure contribution to the impedance of amorphous $Co_{68.2}Fe_{4.3}Si_{12.5}B_{15}$ ferromagnetic wire in a zero external field was measured in two cases. With as-cast wire, changes in the impedance caused by removal of the domain structure in remanent state were measured. Uniform helical anisotropy was induced in the wire by thermal treatment. An inhomogeneous magnetic field applied in a low axial field region caused the formation of a domain structure consisting of two circular domains separated by a single domain wall in this wire. Changes in the impedance caused by removal of this domain structure were measured. In both cases characteristic frequency dependence with a single maximum in the range 1–2 MHz was observed. It is probable that this typical shape originates predominantly from frequency dependence of domain wall oscillations. In the high frequency region, changes in volume magnetization distribution and thus also in transverse permeability can play a significant role. Interpretation based on a stray field generated by axial magnetization inhomogeneities is proposed.

1. Introduction

Two decades ago the giant magneto-impedance (GMI) effect, i.e. large change in impedance caused by an external dc magnetic field, was reported in Co-based amorphous wires [1,2]. Since then the GMI effect has been studied in various materials and has been used in many technical applications [3–5]. Understanding of GMI phenomena combined with understanding of magnetic properties of GMI materials is very important for further progress in technical applications, especially in the field of magnetic field sensors [6–8].

The domain structure of Co-based amorphous microwires is quite simple and thus various theoretical GMI models [9–15] have been tested using these materials. There is strong correlation between the GMI effect and magnetic structure of a magnetic conductor. Typical bamboo structure, an axially magnetized core surrounded by nearly circularly magnetized domains [16,17] in as-cast samples, is determined by stresses induced during solidification, by the cylindrical shape of the wire, and also by its length [18]. This magnetic structure of the conductor can be significantly modified by mechanical stress or by various types of thermal treatment [19,20].

Typical double peak GMI dependence can be observed in as-cast wires but also in wires under applied mechanical stress or after appropriate treatments [2,3,21]. In the case of GMI in a treated wire with circumferential easy direction, additional small peaks due to the presence of helical anisotropy, and possibly due to the axially magnetized core in the low field region can be observed [21,22].

The aim of the study presented in this paper was to provide information about the contribution of the domain structure to the impedance of cylindrical ferromagnetic wire with circular anisotropy. According to GMI theory [5] it is the so-called intermediate frequency regime (between 100 kHz and a few MHz) where GMI originates mainly from the variation of the skin depth due to changes in the effective magnetic permeability caused by the applied dc magnetic field. It will be shown that this is also the frequency range in which domain structure can significantly contribute to the wire impedance.

The impedance of domain structure is defined in this article as the change in the wire impedance caused by the presence of the domain structure. Measurement of the frequency dependence of domain structure impedance is presented for as-cast wire. In this case the domain structure consists of many circular domains. Measurement of this dependence is also presented for the simplest case, in which domain structure consists of two circular domains separated by a single domain wall.

Abbreviations: MIDS, magneto-impedance of domain structure; IDS, impedance of domain structure.

* Corresponding author. Tel.: +421 556022830.

E-mail addresses: Jan.Ziman@tuke.sk (J. Ziman), Viktoria.Suhajova@tuke.sk (V. Šuhajová), Maria.Kladivova@tuke.sk (M. Kladivová).

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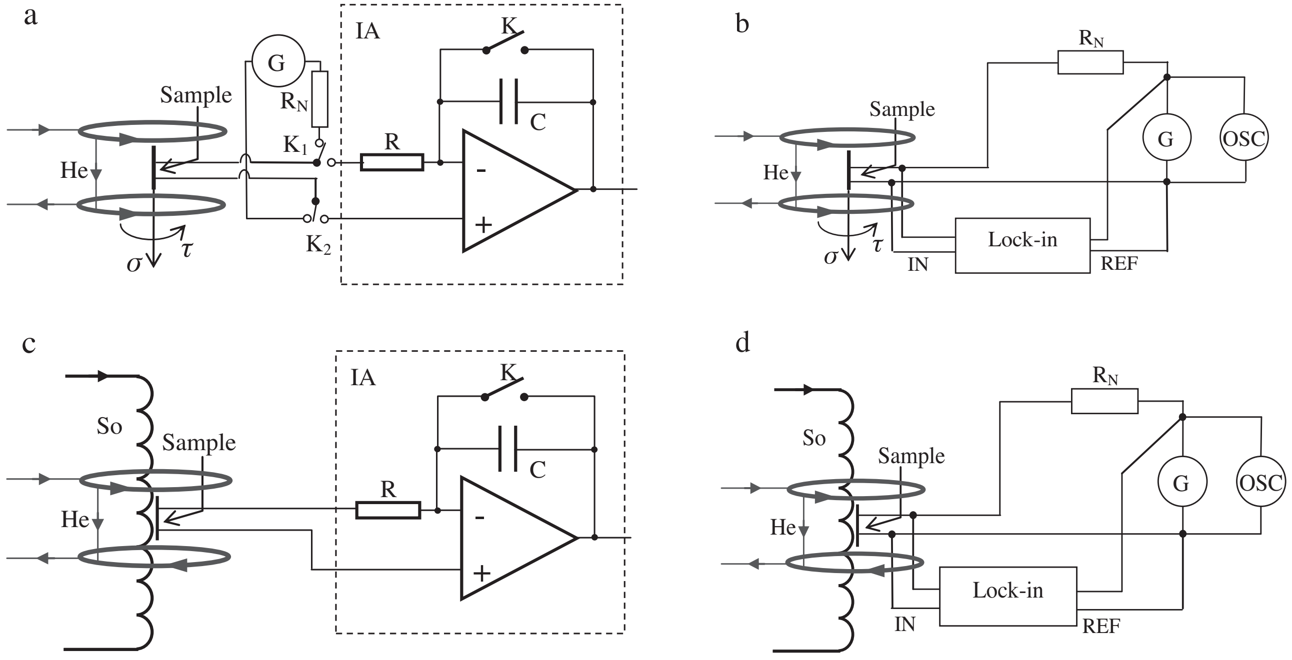

Fig. 1. (a) and (b) Experimental set-ups used for experiment on as-cast wire. (c) and (d) Set-ups used for experiment on treated wire. (a) and (c) Set-ups for circular magnetic flux measurement, and (b) and (d) for impedance measurement. So – solenoid, He – Helmholtz coils, IA – integrating amplifier, Lock-In – lock-in amplifier, G – function generator, OSC – digital oscilloscope, K_1, K_2 – switching keys.

2. Experimental

Amorphous low-magnetostrictive ferromagnetic $Co_{68.2}Fe_{4.3}Si_{12.5}B_{15}$ wire with nominal diameter of 125 µm, prepared using the in-rotating-water-quenching technique, was used for the measurements presented in this paper. The measurements were carried out on as-cast wire and also on a treated sample. The aim of the treatment was to create dominant circular anisotropy with small deviation of easy axis from the ideal circular direction. This state was achieved by treatment in two steps – furnace annealing (460 °C for 3 min) and current annealing (0.5 A for 3 min) with simultaneous application of tensile stress (367 MPa) and torsion of 22 rad/m [19].

The experimental set-ups used for the measurements on as-quenched wire are depicted in Fig. 1(a) and (b). An axial homogeneous magnetic field was created by a pair of Helmholtz coils. Two thin copper wires were attached to the wire (2.7 cm apart) with silver paint and then connected via switches K_1 and K_2 to the input of the integrating amplifier (IA) or to the output of generator G (see Fig. 1(a)). It is also possible to connect a pick-up coil to the IA input for measurement of the axial component of magnetization (not shown in Fig. 1). For the experimental set-up in Fig. 1(b), thin copper wires were connected to the circuit for impedance measurement. Tensile stress σ and torsion τ could be applied simultaneously to the wire during both circular magnetic flux as well as impedance measurements on as-cast wires.

The experimental set-ups used for the measurements on treated wire are depicted in Fig. 1(c) and (d). In this case the axial homogeneous magnetic field was created by solenoid So. A pair of Helmholtz coils (radius $R = 7$ cm) was connected in anti-parallel combination so that it could generate an inhomogeneous magnetic field. The length l of the sample was 6.2 cm so that $l < R$, i.e. the change in this field was nearly linear along the wire, if the zero field point was situated close to the middle of the wire. Thin copper wires were attached to the wire 4 mm apart. The point where the inhomogeneous field created by the Helmholtz coils was equal to zero was approximately in the middle between the points where electric contacts were made. The rest of the circuitry was the same as for the measurements on as-cast wire in Fig. 1(a) and (b).

Magnetic flux or magnetoimpedance vs. axial fields loops presented in this paper were not measured continuously but point by point. A two-step procedure was used for measurement of a single point on these loops.

In the first step the magnetic history of the sample was defined. For instance, if a single point on the ascending branch of the loop was measured, the axial field was changed from its positive maximum value to the negative one and then this field was changed to the measuring value.

In the second step the magnetic flux or impedance corresponding to the magnetic state at the end of the first step was measured.

The advantage of this way of measurement is the possibility of changing procedures in the first step and thus also of modifying the magnetic history. The following modifications of the first step were used for experiments presented in this paper.

2.1. *Experiments on as-cast wire (Fig. 1 (a) and (b))*

After setting the value of measuring axial field H, the circuit containing functional generator was connected to the wire and a rectangular current pulse (about 1 s long) was sent through the wire.

It is clear from Fig. 1(a) and (b) that similar experimental procedures can be used for circular magnetic flux measurements and also for impedance measurements.

For instance, if a single point on ascending branch of the magneto-impedance loop was measured, the axial field was changed from its positive maximum value to the negative one and the value of impedance Z_{max} was measured. Then the axial field was changed to the measuring value and the value of impedance Z_{A1} was measured. After that a rectangular current pulse (which can change the magnetic state of the wire) was sent through the wire and the value of impedance Z_{A2} was measured.