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The Role of Temperature on the Magnetization Process in CoFeZrB/FeCuNbMoSiB Hybrid Ferromagnets

S. Dobák*, J. Füzer and P. Kollár
Institute of Physics, Faculty of Science, P.J. Šafárik University, Park Angelinum 9, 041 54 Košice, Slovakia

The study presents magnetization process behaviour versus operating temperature up to 100 °C in dual-phase ferromagnets in the light of their complex permeability spectra and energy losses from quasi-dc regime up to about 1 MHz upon defined peak induction. The samples consist of two Co- and Fe-based ball-milled-ribbon powders mixed in the same mass ratio. The magnetic characterization has been carried out by a digital hysteresisgraph-wattmeter using complex permeability approach to the linear material. Temperature invoked reduction of anisotropy leads to the decrease of hysteresis losses and significantly affects the low-frequency part of permeability and losses that is ascribed to domain wall movement. The high-frequency behaviour remains unchanged with respect to increase of temperature.

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1. Introduction

In the last years, the classical soft magnets, i.e. alloys and ferrites have been widely subjected to the study of temperature on their magnetic properties [1, 2]. Nonetheless, some specific mechanisms accompanying the magnetization process at different temperatures are still under investigation [2]. Powder compacted bulk magnets are interesting due to their isotropic magnetic behaviour versus versatile 3D complex geometry used in many applications [3] which are often utilized at higher temperatures than room one. Study of temperature influence on magnetization process, in addition evolving with frequency, is therefore necessary. Theoretical modelling [4] envisages a substantial function of preparation of hybrid systems to improve the magnetic response of powder bulk materials by suitable combination of components playing a role of matrix and particles embedded inside. In this study, we investigate two compacted cores prepared by mixing of Fe- and Co-ribbon-based powders.

2. Experimental details

Amorphous soft magnetic alloys $Co_{56}Fe_{16}Zr_8B_{20}$ (at.%) and $Fe_{72.5}Cu_1Nb_2Mo_2Si_{15.5}B_7$ (at.%) in the form of thin ribbons were prepared by melt spinning. Nanocrystalline $Fe_{72.5}Cu_1Nb_2Mo_2Si_{15.5}B_7$ was obtained by annealing of the amorphous precursor at 500 °C for 1 h. The ribbons were separately either milled or cryomilled using a planetary ball mill. The milling was performed under Ar atmosphere with speed of 200 rpm at a ball-to-powder mass ratio of 6:1. Then two samples $(\mathrm{CoFeZrB})_{50}(x\text{-FeCuNbMoSiB})_{50}$ (wt%) were prepared by mixing of CoFeZrB powder in amorphous state with FeCuNbMoSiB powders in as-quenched (x =aq) or nanocrystalline (x =nc) state in the same mass ratio. Such mixtures were consolidated at a pressure of 700 MPa at 590 °C for 2 min. Structural study details can be found elsewhere [5].

The materials were characterized by a digital hysteresisgraph-wattmeter [6] at defined peak inductions (B_p). Energy losses were determined as an area of hysteresis loop $W = \oint H\, dB$ [J/m^3]. The current in primary winding, directly related to the applied magnetic field H, was measured through a calibrated resistor and magnetic induction B via induced voltage on secondary winding. The layout of setup strictly respects $\omega L \ll R$ condition to avoid technical phase shift. The samples were heated in a teflon chamber using a resistive heater. Measurement of temperature was carried out by a Pt resistance sensor placed at the sample surface.

Considering the linear magnetic medium subjected to frequency dependent magnetic field, one can treat the quasi-elliptical hysteresis loops of material from the view of complex permeability approach [6]. If that is justified, the losses at a given B_p versus magnetizing frequency f are related to the real μ' and imaginary μ'' part of complex absolute permeability $\mu' - \mathrm{j}\,\mu''$ by the expression

$$W(B_p, f) = \pi B_p^2 \frac{\mu''(f)}{\mu'^2(f) + \mu''^2(f)} \ [\mathrm{J/m^3}]. \quad (1)$$

This approach permits us to characterize the material at higher defined induction levels compared to impedance spectroscopy [7, 8] that is used for measurements at low magnetic fields.

3. Results and discussion

The hysteresis loops obtained in wide frequency band from several Hz up to about 1 MHz are of quasi-elliptical shape. Therefore, the linear approximation of material is physically meaningful, which permits to

*corresponding author; e-mail: samuel.dobak@student.upjs.sk

assess the complex permeability parts using Eq. (1). Real (μ_r') and imaginary (μ_r'') relative (reduced by magnetic constant μ_0) permeability components versus magnetizing frequency measured in two powder cores $(CoFeZrB)_{50}(aq\text{-}FeCuNbMoSiB)_{50}$ and $(CoFeZrB)_{50}$ $(nc\text{-}FeCuNbMoSiB)_{50}$ under the different temperatures at $B_p = 10$ mT are illustrated in Figs. 1 and 2, respectively. The open points with lines were obtained at 23 °C and full points with lines at 100 °C. These spectra are of a relaxation-dispersion type with the frequency stable μ_r' up to about 200 Hz and a single peak in μ_r'' located at $f_0 \approx 7$ kHz. The spectra are connected to the response of magnetic moments, inside the both domain walls and magnetic domains, to the applied ac magnetic field and their ability to follow it. Such dynamic behaviour is affected by domain walls stiffness, their dimensions, pinning sites distribution, magnetic anisotropy and damping sources for the viscous motion of magnetic moments [9].

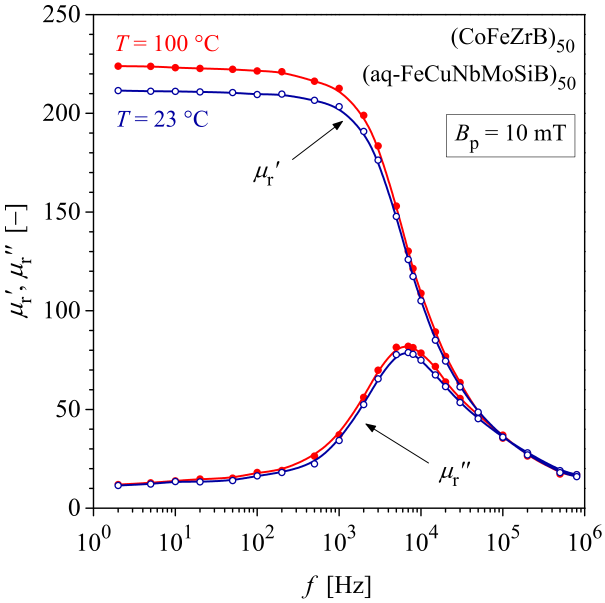

Fig. 1. Complex permeability spectra of sample with composition $(CoFeZrB)_{50}(aq\text{-}FeCuNbMoSiB)_{50}$ at temperature of 23 °C and 100 °C at $B_p = 10$ mT.

The electrical resistivity of prepared cores (255 $\mu\Omega$cm for the material with aq-FeCuNbMoSiB and 330 $\mu\Omega$cm for the core containing nc-FeCuNbMoSiB) is due to many possible electrical contacts between the particles that have the electrical resistivity of used ribbons ($\rho \approx 120$–170 $\mu\Omega$cm). Slightly lower resistivity of material with aq-FeCuNbMoSiB powder could be ascribed to the larger ability of amorphous material to the plastic deformation during the compaction. According to the resistivity and observation of permeability dispersion in kHz region, one can conclude that the eddy currents play a major role at the damping of domain walls in these materials.

Comparing to the measurement at room temperature, the temperature of 100 °C causes an increase in dc real permeability of approximately 7% in case of the sample

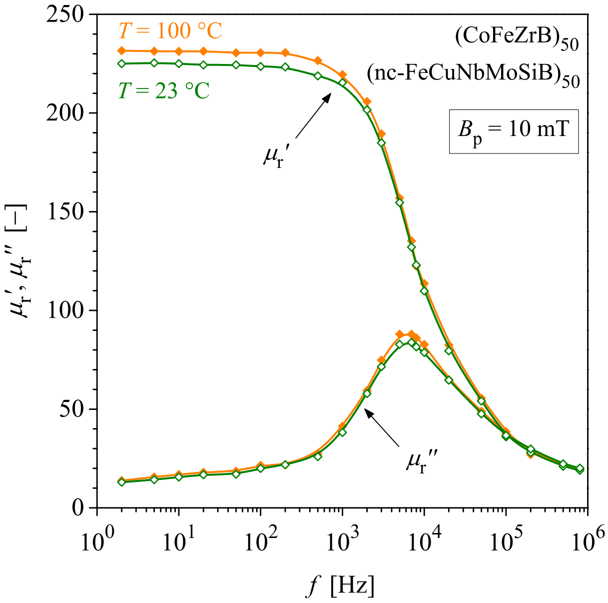

Fig. 2. As in Fig. 1, but for the composition $(CoFeZrB)_{50}(nc\text{-}FeCuNbMoSiB)_{50}$.

with as-quenched $Fe_{72.5}Cu_1Nb_2Mo_2Si_{15.5}B_7$ and about 2% in the sample with the same addition of nanocrystalline alloy. The temperature has very small effect on imaginary component of permeability and causes a little increase in μ_r'' in the region of its peak without the change of its position.

The increase of μ_r' at low frequencies (dc–2 kHz) is a result of decreasing anisotropy induced in samples processing. Anisotropy constant can be determined as an area to the left from hysteresis loop in the first quadrant of loop plane [10]. From the difference in areas for loops at $B_p = 10$ mT taken at room temperature and 100 °C, the anisotropy constant reduction is estimated as $\Delta K_T \approx 9$ mJ/m^3 for $(CoFeZrB)_{50}(aq\text{-}FeCuNbMoSiB)_{50}$ sample and $\Delta K_T \approx 3$ mJ/m^3 for $(CoFeZrB)_{50}(nc\text{-}FeCuNbMoSiB)_{50}$ sample. After the exposure to temperature $T = 100$ °C, the permeability decreases to the initial values and therefore can be concluded that the removing of a part of induced anisotropy is reversible in the investigated temperature range. The permeability of nanocrystalline alloys can be negatively affected by weakening of exchange coupling between nanocrystallites [2], but features of this effect are not observed here.

The wideband energy loss response to magnetizing frequency at $B_p = 10$ mT in two hybrid magnets against temperature of 23 °C and 100 °C is provided in Figs. 3 and 4, respectively. Loss mechanism attributed to frictional behaviour of domain walls on hindering and pinning obstacles of different nature is lumped into the hysteresis losses W_{hyst} that can be obtained from measured losses $W(f)$ by their extrapolation to dc regime $W_{hyst} = \lim_{f\to 0} W(f)$. So-extracted W_{hyst} losses at two temperatures are depicted in Figs. 3 and 4 by dashed

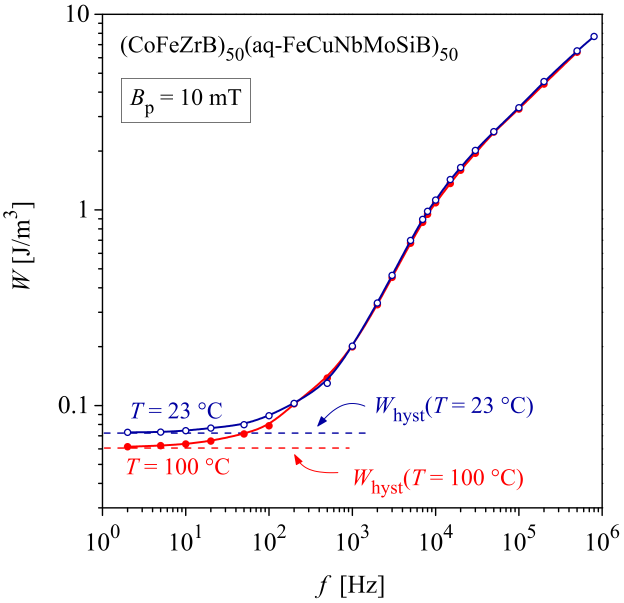

Fig. 3. Wideband energy loss behaviour of sample with composition $(CoFeZrB)_{50}$(aq-FeCuNbMoSiB$)_{50}$ at temperature of 23 °C and 100 °C at $B_p = 10$ mT.

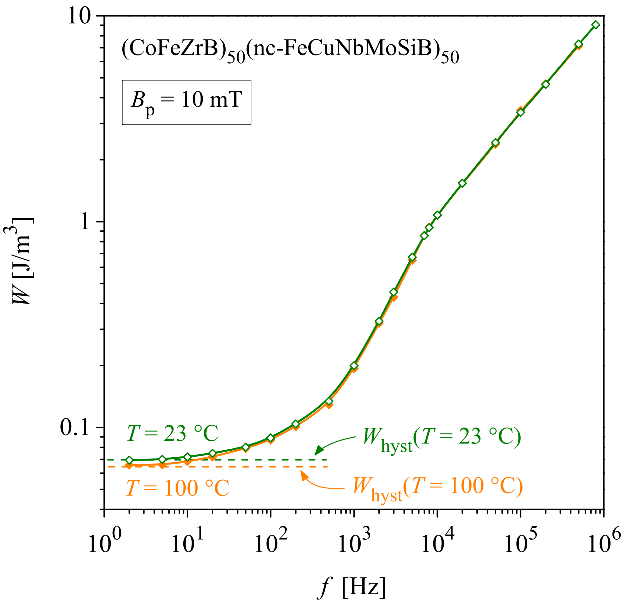

Fig. 4. As in Fig. 3, but for the composition $(CoFeZrB)_{50}$(nc-FeCuNbMoSiB$)_{50}$.

lines. From these results, it can be seen that the temperature affects the low-frequency part of energy losses and particularly suppresses the hysteresis losses. The decrease of W_{hyst} is more pronounced (about 10 mJ/m^3) in the sample with as-quenched $Fe_{72.5}Cu_1Nb_2Mo_2Si_{15.5}B_7$ compared to the addition of same alloy in nanocrystalline state that results in hysteresis loss reduction of 5 mJ/m^3. In the region beyond several tens kHz, the energy losses are temperature independent.

4. Conclusions

The wideband complex permeability and energy losses in two ribbon-powder-based hybrid ferromagnets are investigated to determine the influence of operating temperature on magnetization process. It is found that hysteresis loss part, connected to the static contribution of domain walls, is noticeably affected by temperature of 100 °C, while the high-frequency part is temperature independent. Under the larger temperature, low-frequency real permeability part increases. From the results, the anisotropy constant and hysteresis loss reduction with temperature are achieved.

Acknowledgments

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