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Complex Permeability After-Effect and Analysis of Power Losses in Ferromagnetic Co-Based Amorphous Alloy

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Complex permeability ($\mu = \mu_1 - \mathrm{i}\mu_2$) after-effect of near-zero magnetostrictive CoFeCrSiB amorphous alloy was investigated in magnetic field $H(t) = H_0 \exp(\mathrm{i}2\pi f t)$ after demagnetization. For frequencies f from 200 Hz to 2000 Hz and for the small amplitude $H_0 < H_{\mathrm{cr}}$ we observed practically constant both real μ_1 and imaginary part μ_2 of permeability. A measured small decrease in the real part μ_1 and increase in the imaginary part μ_2 with frequency f were theoretically calculated for a quadratic form of a domain wall potential $E_{\mathrm{S}}(x) = \frac{1}{2}\alpha x^2$. The calculated loss factor $\tan\delta = \mu_2/\mu_1$, which is small at amplitude $H_0 < H_{\mathrm{cr}}$, corresponds to power losses due to eddy currents induced around reversibly moving domain walls.

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1. Introduction

After demagnetization procedure the positions of the domain walls (DWs) are determined by the static pinning potential $E_0(x)$ (x is a DW displacement). The magnetic after-effect (MAE) of permeability $\mu = \mu_1 - \mathrm{i}\mu_2$ is related to the stabilization potential $E_{\mathrm{S}}(x,t) = E_{\mathrm{S}}(x)G(t)$, separated to $E_{\mathrm{S}}(x) = \frac{1}{2}\alpha x^2$, for small $x < d$ (d is a DW thickness) and to time relaxation function $G(t)$, when an external magnetic field $H(t) = H_0 \exp(\mathrm{i}\omega t)$ with small amplitude $H_0 < H_{\mathrm{cr}}$ is applied. The MAE of the complex permeability μ can be expressed as a change of its reciprocal value (reluctivity) $r = 1/\mu = r_1 + \mathrm{i}r_2$: $\Delta r(t) = r(t_2) - r(t_1)$ at time interval from t_1 to t_2 after demagnetization [1].

2. Theoretical model

From the theoretical point of view it is a very interesting idea of Döring that the moving DW exhibits an inertia. The mass of the DW has its origin in the angular momenta of the spins forming the wall [2]. We consider the equation of motion for 180° DW:

$$m\frac{\mathrm{d}^2x}{\mathrm{d}t^2}+\beta\frac{\mathrm{d}x}{\mathrm{d}t}+\alpha x=2\mu_0 M_\mathrm{s} H, \tag{1}$$

where m is the mass of the DW per unit area, β — the damping coefficient, α — the restoring coefficient. The term $2\mu_0 M_\mathrm{s} H$ on the right side of the equation represents the pressure acting on the 180° DW. $H(t)=H_0\exp(\mathrm{i}\omega t)$ is applied with a small amplitude H_0 less than critical H_cr, the solution of Eq. (1) can be found

$$x(t)=\frac{2\mu_0 M_\mathrm{s} H_0/\alpha}{1-(m/\alpha)\,\omega^2+\mathrm{i}\,(\beta/\alpha)\,\omega}\exp(\mathrm{i}\omega t). \tag{2}$$

In the demagnetized state, the displacement of the 180° DW x is connected with the magnetic polarization: $J(t)=2\mu_0 M_\mathrm{s} x(t)$, and then the expression for complex permeability can be obtained

$$\mu(\omega)=\mu_1-\mathrm{i}\mu_2=\frac{J(t)}{H(t)}=\frac{\mu_\mathrm{s}\exp(-\mathrm{i}\delta)}{\sqrt{[1-(\omega^2 m/\alpha)]^2+(\omega\beta/\alpha)^2}}, \tag{3}$$

where $\mu_\mathrm{s}=4\mu_0^2 M_\mathrm{s}^2/\alpha$ states for static permeability. The loss factor is

$$\tan\delta=\mu_2/\mu_1=\frac{\omega\beta/\alpha}{1-\omega^2 m/\alpha}. \tag{4}$$

3. Experiment

Near zero magnetostrictive amorphous alloy $Co_{66.6}Fe_{3.9}Cr_{6.9}Si_{7.6}B_{15}$ in as-cast state with the coercive field H_c = 0.6 A m^{-1} was used in experiments. Ribbon-shaped sample 5 mm wide was used as a core of toroidal coil with the mean diameter of 22 mm. The MAE was measured between t_1 = 30 s and t_1 = 300 s after demagnetization by an AC magnetic field decreasing in 5 s from maximum amplitude to zero [3].

4. Results and discussion

The dependences of real μ_1 and imaginary μ_2 parts of $Co_{66.6}Fe_{3.9}Cr_{6.9}Si_{7.6}B_{15}$ alloy on the amplitude of applied field H exhibit perminvar behaviour (Fig. 1). For the amplitude $H_0 < H_\mathrm{cr}$ = 1.4 A m^{-1} DWs remain localized. In case of periodic movement of DWs $x(t)=x_0\exp(\mathrm{i}(\omega t-\delta))$ forced by external driving field $H(t)=H_0\exp(\mathrm{i}\omega t)$, the x_0 is small, taking into account a ratio $H_\mathrm{c}/H_\mathrm{cr}$ = 5. We can find a small decrease in the real part μ_1 with frequency $f=\omega/2\pi$: $[\mu_1(200\ \mathrm{Hz})-\mu_1(2000\ \mathrm{Hz})]/\mu_1(200\ \mathrm{Hz})$ = 1.5% (Fig. 2a). In limit case $\omega\to 0$, μ_1 goes to $\mu_\mathrm{s}=4\mu_0^2 M_\mathrm{s}^2/\alpha$. The imaginary part μ_2 increases with the frequency f (Fig. 2a). As it results from Eq. (3), μ_2 is

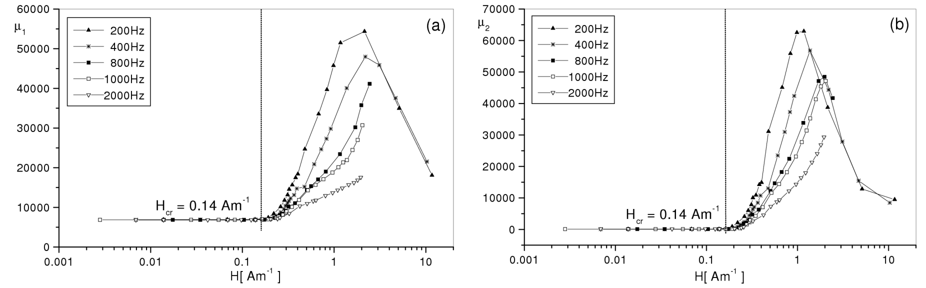

Fig. 1. (a) Dependence of the real part of permeability μ_1 on amplitude of applied magnetic field. (b) Dependence of the imaginary part of permeability μ_2 on amplitude of applied magnetic field. The frequencies of measurements and critical amplitude H_{cr} are displayed.

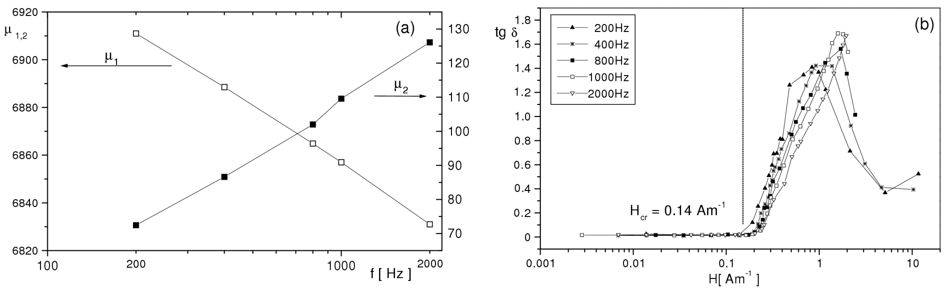

Fig. 2. (a) Real μ_1 and imaginary μ_2 part of permeability dependence on frequency of applied magnetic field, with amplitude less than critical H_{cr}. (b) Dependence of the loss factor $\tan\delta = \mu_2/\mu_1$ on amplitude of applied magnetic field. The frequencies of measurements and critical amplitude H_{cr} are displayed.

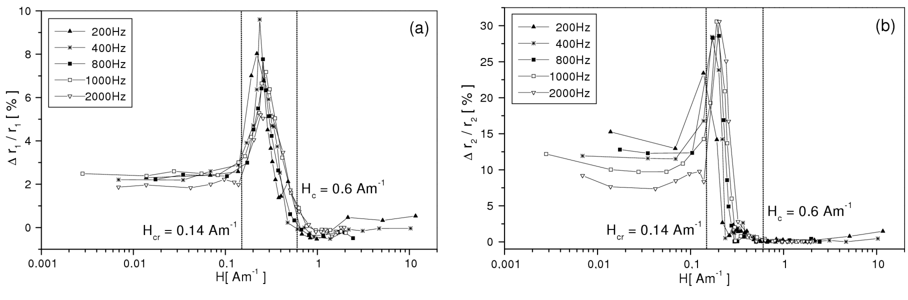

Fig. 3. Relative change of the real part $\Delta r_1/r_1$ (a) and imaginary part $\Delta r_2/r_2$ (b) of the reciprocal permeability (reluctivity) $r = 1/\mu$ on amplitude of magnetic field. The critical amplitude H_{cr} and coercivity H_{c} are displayed.

proportional to damping coefficient β and goes to zero in limit case $\omega \to 0$. The calculated loss factor $\tan\delta = \mu_2/\mu_1$ (Eq. (4)), reflecting the power losses, increases with frequency similarly as μ_2 (Fig. 2). In the range where $H_{\mathrm{cr}} < H_0$, we observe the rapid increase in permeability μ_1 and μ_2 (Fig. 1). The maxima of μ_1 and μ_2 are shifted towards higher field intensity and their values decrease with frequency. This indicates a substantial influence of frequency dependent eddy currents induced during the Barkhausen jumps. We register a huge increase in power losses connected with this irreversible DW movement (Fig. 2b). MAE of real part of reluctivity $\Delta r_1/r_1 = 2\%$ in $H_0 < H_{\rm cr}$ (Fig. 3a). MAE of imaginary part of reluctivity $\Delta r_2/r_2$ decreases with frequency from 15% to 7% in $H_0 < H_{\rm cr}$ (Fig. 3b). When amplitude H_0 exceeds critical $H_{\rm cr}$, we observe sharp peaks in MAE dependences of $\Delta r_1/r_1$ and $\Delta r_2/r_2$ and rapid decrease in both MAE dependences to zero in interval of amplitude $H_{\rm cr} < H_0 < H_{\rm c}$ (Fig. 3).

5. Conclusion

There are two processes affecting the power losses in $H_0 < H_{\rm cr}$: (1) stabilization of the domain walls, (2) eddy currents induced during reversible periodic movement of domain walls. When amplitude H_0 exceeds critical $H_{\rm cr}$, the destabilization of domain walls occurs starting with irreversible Barkhausen jumps followed by maximum of MAE.

Acknowledgments

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References

[1] H. Kronmüller, *Philos. Mag. B* **48**, 127 (1983).
[2] S. Chikazumi, *Physics of Magnetism*, Wiley, New York 1964.
[3] P. Vojtaník, J. Kravčák, R. Varga, *J. Magn. Magn. Mater.* **157/158**, 175 (1996).