DYNAMICS OF MAGNETIC DOMAIN WALLS IN THIN FERROMAGNETIC LAYERS AND WIRES

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1. Introduction

The amorphous ferromagnetic alloys prepared by rapid quenching of the melt on rotating copper cylinder are well-known materials for recent 40 years. Very long amorphous ferromagnetic samples with strong axial anisotropy are used for measurements to avoid the demagnetization effect. The samples have variable width up to 10 cm. Generally the total magnetic energy of the sample decreases to its minimum if the sample splits into reversely magnetized domains separated by a longitudinal magnetic 180° domain wall. Nevertheless the total domain wall energy must be taken into account, which increases with the sample length. For this reason if some critical sample length is exceeded then the transformation of 180° domain wall (DW) into the head-to-head domain wall (HDW) type known in very thin ferromagnetic samples occurs [1]. The amorphous wires of various compositions with the diameter 125 μm are prepared by rapid quenching of the melt in rotating water [2]. The magnetostriction coupled with frozen-in internal stresses is decisive for the domain wall structure building in amorphous wire. The domain wall dynamics during magnetization reversal of amorphous wire FeSiB with high positive magnetostriction is described by means of the core-shell model assuming residual radial tensile stresses in the as-cast state [2]. The appearance of a square-shaped low field hysteresis loop is ascribed to the movement of a single magnetic domain wall along an internal core of the FeSiB wire with probably axial magnetization [3].

Further very important category are thin amorphous glass coated wires with the diameter less than 10 μm, so called microwires, prepared by Taylor-Ulitovski technique [4].

Actually the deposited very thin ferromagnetic structures with the diameter of the order of 1 μm are very prospective from practical and theoretical point of view.

2. Theoretical overview

Each model of ferromagnetic domain structure starts from minimization of total magnetic energy of the sample consisting of magnetostatic energy and magnetoelastic energy [5]. Let the sample be divided into two reversally magnetized domains separated by a single thin 180° domain wall. This can be usually observed in the samples with strong uniaxial magnetic anisotropy, where the magnetization $\boldsymbol{M}$ is aligned with a longitudinal sample axis. Nevertheless it is necessary to involve the magnetostatic energy of surface charges originated from local magnetization divergence at the area where the domain wall crosses the sample surface. The micromagnetic calculations in a very thin sample revealed that the internal structure of the 180° domain wall produces surface vortices to avoid magnetostatic energy of surface charges [6].

2.1 Eddy current model

In the case of very long samples of thickness d about 20 μm with the strong uniaxial magnetic anisotropy the magnetization reversal occurs by the movement of a single 180° domain wall (DW) with the velocity v. The moving DW induces eddy current flow described by current density vector $\boldsymbol{j}$ circulating around the wall:

$$\mathrm{rot}\,\boldsymbol{j} = -\frac{\mu_0}{\rho}\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t}, \tag{1}$$

where ρ is electric resistivity. If DW is pressed (accelerated) by the external field strength H, which is antiparallel with initial saturation magnetization M_s and damped (decelerated) by the induced eddy current field strength H_e acting on the DW (eddy current damping effect) and the inertia of DW is negligible, the equilibrium $H_e = -H$ is established almost instantly. From the density vector $\boldsymbol{j}$ calculation Eq. (1) results the eddy current loss per unit length of DW:

$$P = \rho \int \boldsymbol{j}^2 dV, \tag{2}$$

On the other hand the change of magnetostatic energy during DW motion corresponds to the rate $P = 2\mu_0 M_s H v d$, which is equal to Eq. (2). From the law of energy conservation results that the eddy current damping has the viscose character: $v = S.H$, where the constant of proportionality S is the DW mobility [7].

2.2 Landau-Lifschitz-Gilbert equation

Numerical micromagnetic simulations of domain wall motion in very thin micro- and nano-wires showed that the transverse wall or vortex wall is formed during the nucleation and the expansion of reversed domains [8]. The magnetization reversal process in long microwires with the strong axial magnetic anisotropy takes place by the movement of a single head-to-head domain wall (HDW) with the velocity v, which is calculated by means of Landau-Lifschitz-Gilbert (LLG) equation of motion [8]:

$$\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} = \gamma\left(\boldsymbol{M}\times\boldsymbol{H}\right) - \frac{\alpha}{M_s}\left(\boldsymbol{M}\times\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t}\right), \tag{3}$$

where the γ is gyromagnetic ratio, α is Gilbert damping constant. The solution of Eq.(3) gives the theoretical maximum of HDW velocity, so called Walker velocity [9]. The numerical solution of LLG equation together with the condition of minimum total magnetic energy determine the state when the transverse HDW or the vortex HDW in Fig. (1) is convenient [10].

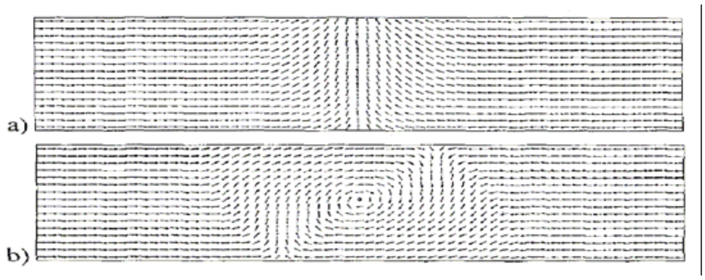

Fig.1: *The 2D model of a) the transverse HDW and b) the vortex HDW* [10].

3. Experimental results and discussion

Sixtus-Tonks experiments have revealed in the case of very long (30 cm) amorphous wire $Fe_{77.5}$ $Si_{7.5}$ B_{15} the change of the DW mobility in lower axial field strength H=22 A/m and in higher axial field strength H=35 A/m, see Fig. (2). Three regions with different DW dynamics can be recognized: I. region, where the depinning of DW takes place. The analysis of the shape of Barkhausen impulse induced during the depinning of DW has shown the conical DW shape [11]. The 180° DW movement in I. region has not the viscose character. II. region, the shape of 180° DW is planar and DW movement has the viscose character. III. region, the increase of the DW mobility indicates the weak damping process connected probably with DW transformation from the 180° DW into the head-to-head domain wall.

The change of the DW mobility in the higher axial field strength H=300 A/m has been also observed in amorphous microwire Fe_{76} Si_9 B_{10} P_5, see Fig. (3), by Richter, Varga et al. [12]. In this case the HDW transformation has been detected from the transverse HDW into the vortex HDW. The type of HDW can be identified by application of additional transversal magnetic field during Sixtus-Tonks experiment.

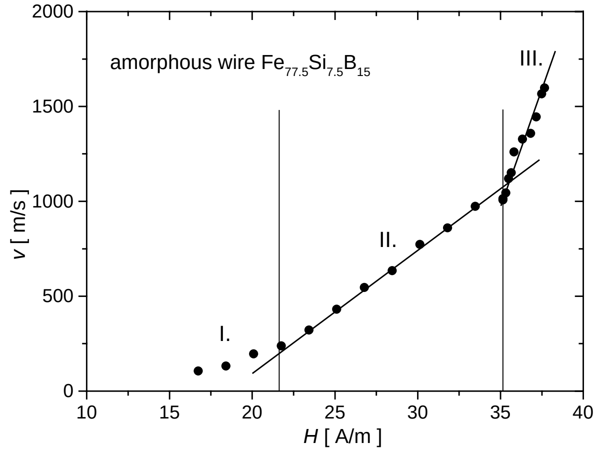

Fig.2: *Dependence of DW velocity on axial magnetic field strength in $Fe_{77.5}$ $Si_{7.5}$ B_{15} amorphous wire of diameter d=125μm.*

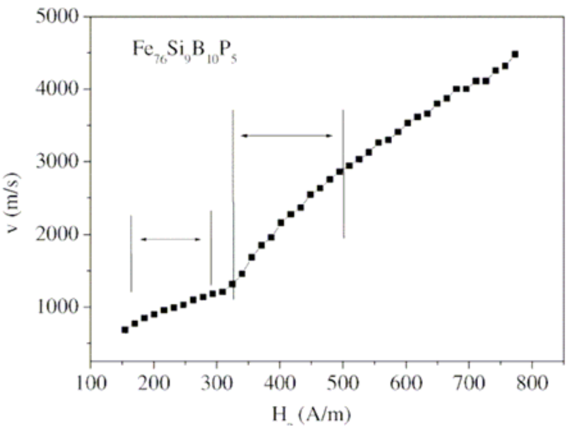

Fig.3: *Dependence of DW velocity on axial magnetic field strength in Fe_{76} Si_9 B_{10} P_5 amorphous wire of diameter 45μm. The ferromagnetic nucleus diameter d=14μm* [12].

4. Conclusion

The variation of DW mobility and DW shape in amorphous ferromagnetic wire $Fe_{77.5}$ $Si_{7.5}$ B_{15} has been presented in the paper. The viscose character of DW motion $v = S.(H-H_0)$ has been verified in the region of the lower magnetic field strength 22 A/m $\leq H \leq$35 A/m, where it results from the eddy current model and also in the region of higher magnetic field strength $H \geq$35 A/m, where it results from the solution of the LLG equation of motion. The critical field strength in II. region is H_0=18 A/m an in III. region is H_0=32 A/m.

The experimental results of other authors performed on amorphous microwire Fe_{76} Si_9 B_{10} P_5 [12] have shown that the viscose character of DW motion is also observed in the case of the transverse HDW in the region of the lower magnetic axial field strength 150 A/m $\leq H \leq$300 A/m as well as in the case of the vortex HDW in the region of the higher magnetic axial field strength 300 A/m $\leq H$. Once the DW movement starts, the DW shape remains the same till the magnetization reversal is completed [8]. The Walker velocity limit [9] has not been reached in any wire under this study.

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References:

[1] R. D. McMichael, M. J. Donahue: *IEEE Trans. Magn.*, **Vol. 33**, 4167 (1997).
[2] M. Vazquez: *Physica B*, Vol. **299**, 302 (2002).
[3] J. Kravčák, L. Novák, A. Zentko: *Czechoslovak Journal of Physics*, **Vol. 52**, 175 (2002).
[4] V. S. Larin, A. V. Torcunov, A. Zhukov, J. Gonzáles, M. Vazquez, L. Panina: *J. Magn. Magn. Mater.,* **Vol. 249**, 39 (2002).
[5] S. Chikazumi: *Physics of magnetism*, John Wiley&Sons, New York (1964).
[6] W. Rave, A. Hubert: *J. Magn. Magn. Mater.,* **Vol. 184**, 179 (1998).
[7] J. Kravčák: *Acta physica slovaca*, **Vol. 56**, 153 (2006).
[8] H. Forster, T. Schrefl, W. Scholtz, D. Suess, V. Tsiantos, J. Fidler: *J. Magn. Magn. Mater.*, **Vol. 249**, 181 (2002).
[9] N. L. Schryer, L. R. Walker: *Journal of Applied Physics*, **Vol. 45**, 5406 (1974).
[10] R. D. McMichael, M. J. Donahue: *IEEE Trans. Magn.*, **Vol. 33**, 4167 (1997).
[11] J. Kravčák: *Acta electrotechnica et informatica*, Vol. **2**, 82 (2002).
[12] K. Richter, R. Varga, G. Infante, et al.: *IEEE Trans. Magn.*, **Vol. 46**, 210 (2010).