ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2010, Vol. 74, No. 10, pp. 1459–1461. © Allerton Press, Inc., 2010.
Original Russian Text © E.G. Ekomasov, Sh.A. Azamatov, R.R. Murtazin, A.M. Gumerov, A.D. Davletshina, 2010, published in Izvestiya Rossiiskoi Akademii Nauk. Seriya Fizicheskaya, 2010, Vol. 74, No. 10, pp. 1520–1522.

Simulation of the Nonlinear Dynamics of Magnetic Inhomogeneities in Real Magnets

E. G. Ekomasov, Sh. A. Azamatov, R. R. Murtazin, A. M. Gumerov, and A. D. Davletshina
Bashkir State University, Ufa, 450074 Russia
e-mail: ekomasoveg@bsu.bashedu.ru

Abstract—The dynamics of domain walls (DW) in an infinite ferromagnet containing a flat layer with parameters of magnetic anisotropy and exchange interaction differing from the bulk values was investigated. The dependences of the minimum velocity of DW transmission through the defect region and the translational and pulsation modes of DW fluctuations on the parameters describing the inhomogeneity of magnetic anisotropy and exchange interaction were found.

DOI: 10.3103/S1062873810100412

INTRODUCTION

One line in theoretical investigations of the influence of defects on magnetic inhomogeneity is considering (within thermodynamic theory) the possibility of a spatial dependence of the parameters of the materials under study [1]. Since exact (microscopic) calculation is generally quite difficult, we have to model the functions describing the parameters of inhomogeneous material (e.g., the magnetic anisotropy constant, the exchange interaction parameter, and so on). Approximation of a defect in the form of a flat (or platelike) magnetic inclusion, either infinitely thin (i.e., with a thickness on the same order of magnitude as the interatomic distance) or having a finite thickness, is often used for ferromagnets [2]. The effect of flat magnetic inclusions on the static and certain dynamic properties of magnetic inhomogeneities has been studied both analytically and using numerical methods [2–6]. Perturbation theory has been well developed for this equation [7]; nevertheless, numerical methods must be used for arbitrary changes in the parameters of materials [8]. Some experiments have been aimed at investigating the changes in the structure of a domain wall (DW) when the latter intersects a defect [9]. An interesting problem is the DW dynamics in an infinite ferromagnet with a flat layer whose parameters of magnetic anisotropy and exchange interaction differ from the corresponding bulk values.

Let us consider an infinite ferromagnet whose crystallographic axes (a,b,c) coincide with the Cartesian coordinate axes (x,y,z). Taking into account the exchange interaction, anisotropy, Zeeman energy, and damping in the magnet energy density, we can write the equation of motion for magnetization in angular variables, $m = m(0,\cos\theta,\sin\theta)$, in the dimensionless form [3]:

$$A(\tilde{x})\frac{\partial^2\theta}{\partial\tilde{x}^2} - \ddot{\theta} - \frac{K(\tilde{x})}{2}\sin 2\theta + A'(\tilde{x})\frac{\partial\theta}{\partial\tilde{x}} = h\sin\theta + \alpha\dot{\theta}, \quad (1)$$

where $A(\tilde{x})$ and $K(\tilde{x})$ are functions determining the distributions of the exchange interaction and anisotropy inhomogeneities, respectively; h is the external magnetic field; α is the damping constant; $\tilde{t} = t/\left(\frac{\delta_0}{c}\right)$, $\tilde{x} = x/\delta_0$, δ_0 is the width of static Bloch DW; and c is the limiting Walker velocity of stationary motion [3]. Equation (1) is a modified sine-Gordon equation with variable coefficients [7].

The most interesting situation is when the size of a DW and the dimensions characterizing the parameter inhomogeneity are on the same order of magnitude. In this case, the DW shape should change considerably when passing through an inhomogeneous region. We shall describe the inhomogeneity of parameters K and A by rectangular and triangular functions [2, 3]:

$$f(\tilde{x}) = \begin{cases} 1, & |\tilde{x}_2 - \tilde{x}_1| > W \\ f, & |\tilde{x}_2 - \tilde{x}_1| \le W \end{cases}$$

$$f(\tilde{x}) = \begin{cases} 1, |\tilde{x}_2 - \tilde{x}_1| > W \\ 1 - \frac{2f}{W}\tilde{x}, \quad \tilde{x}_1 \le \tilde{x} \le \tilde{x}_1 + W/2 \\ 1 - f + \frac{2f}{W}\tilde{x}, \quad \tilde{x}_1 + W/2 \le \tilde{x} \le \tilde{x}_2, \end{cases} \quad (2)$$

where W is the defect width and $f = \{K, A\}$ are the values of the parameters in the defect region. DW motion through the defect region was analyzed by solving Eq. (1) numerically using an explicit integration scheme. The algorithm for the numerical solution of

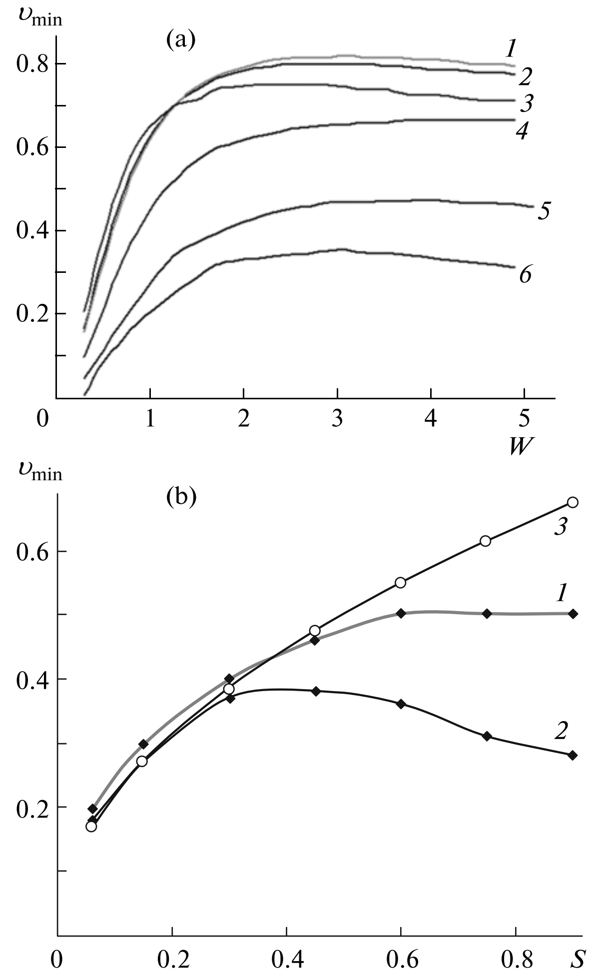

Fig. 1. Dependences of υ_{min} on (a) parameter W at (*1*) $K = -1.2$, $A = 3$; (*2*) $K = -1.2$, $A = 2.5$; (*3*) $K = -1.2$, $A = 2$; (*4*) $A = 1.5$, $K = -0.2$; (*5*) $A = 1.5$, $K = 0.4$; and (*6*) $A = 1.5$, $K = 0.6$ and (b) parameter S for the case $K = 1$ and exchange interaction inhomogeneity (*1*) of rectangular shape, (*2*) of triangular shape, and (*3*) obtained from the formula $\upsilon_{min} = \sqrt{\frac{S}{2}}$.

Eq. (1) was as follows: The magnetization distribution at the initial instant was set as a Bloch DW, $\theta_0(x) = 2\arctan\left(e^{\tilde{x}}\right)$, localized far from the defect region. The boundary conditions took the form $\theta(\pm\infty) = 0, \pi$ and $\theta'(\pm\infty) = 0$. Using a coordinate net [−1000 ... 1000] and taking time as an iterative parameter (with due regard for the condition of explicit scheme convergence), we then calculated the state of the system at the next instant and obtained the main characteristics of the dynamic DW from this state. The DW was accelerated by an external magnetic field to the stationary velocity $\upsilon_{pre} = \frac{\chi}{\left(1+\chi^2\right)^{1/2}}$, where $\chi = h/\alpha$, and crossed the defect region. All calculations were performed for the case $\alpha = 2 \times 10^{-2}$.

The desired dependences $\theta(\tilde{x}, \tilde{t})$ for different values of DW velocity and the parameters and shape of anisotropy and exchange interaction inhomogeneities were found by numerical calculation. Depending on the initial stationary velocity value, a DW either crosses the defect region or is captured by it. We calculated the minimum DW velocity υ_{min} that is necessary to overcome the defect region. Its dependence on the parameter W for different K and A values is shown in Fig. 1a. Note that the numerical results for minor defects are in good agreement with the analytical results obtained in [3] within the perturbation theory. One can also see in Fig. 1a that, in contrast to the data in [3], when the parameters A and K are large, the effect on υ_{min} from a change in their values is different. For example, at large values of $(1 - K)$, a major change in A affects υ_{min} only slightly. The noticeable (as compared to the analytical results) change in the dependence of υ_{min} for large A, K, and W values can be explained by the more exact consideration (in our case) of the change in DW structure due to interaction with a defect.

We also found the dependence of υ_{min} on the area S according to the rectangular and triangular functions (2) describing the parameter inhomogeneity (Fig. 1b). It can be seen that at small S areas, the υ_{min} values are quite similar in both cases; i.e., we may assume that the υ_{min} is affected considerably (as in the case $A = 1$, considered previously in [10]), due more to the size of the exchange interaction inhomogeneity than to its shape. Note also that for minor defects, the υ_{min} value is similar to the analytical value: $\upsilon_{min} = \sqrt{\frac{S}{2}}$. With an increase in parameter S (in our case, due to an increase in A at constant W, which leads to a significant change in DW structure), the υ_{min} values differed appreciably.

The change in DW structure for the case $\upsilon < \upsilon_{min}$, in which DW was trapped in the defect region, was also considered. Damping (similar to harmonic) DW oscillations, accompanied by a change in DW width over time, were observed in the defect region. When approximating the temporal dependence of DW center oscillations by an exponential function, we found that the observed damping decrement was much larger than that set in Eq. (1). This indicates that a large part of DW kinetic energy is lost through radiation. The temporal dependence of the DW center coordinate also yields the translational frequency of DW vibrations, ω_T (Fig. 2a). As in the case $A = 1$ considered in [11], at $K = 1$ (minor defects) the dependence $\omega_T(A)$ is described well by the analytical dependence obtained within perturbation theory [3]. The ω_T values begin to significantly decrease (in comparison with the analytical result) with an increase in the parameters of exchange interaction inhomogeneity; this can be explained by our more careful consideration of the

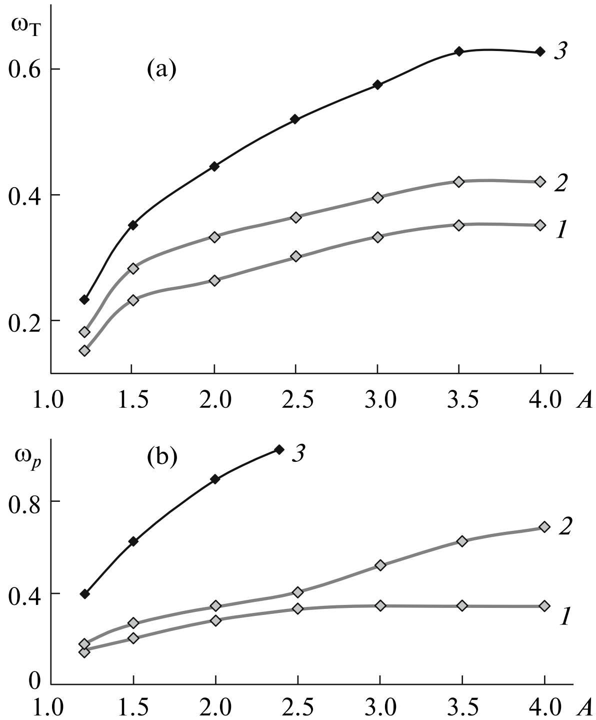

Fig. 2. Dependences of (a) ω_T and (b) ω_F on parameter A for $K = 1$; $\upsilon = 0.05$; and $W =$ (*1*) 0.3, (*2*) 0.5, and (*3*) 1.

change in DW structure due to DW–defect interaction. The temporal dependence of DW width yields the pulsation frequency ω_p of DW fluctuations (Fig. 2b). Note that this value exceeds the translational frequency, just as the theory in [12] predicted. The description of the anisotropy and exchange interaction inhomogeneities by triangular functions leads to similar dependences of the translational and pulsation modes of DW fluctuations on the parameters K and A. Along with $\upsilon_{\min}$, the ω_T and ω_p values for minor defects depend to a greater extent on the parameter S rather than on the shape of function (2).

REFERENCES

1. Vonsovskii, S.V., *Magnetizm* (Magnetism), Moscow: Nauka, 1971.
2. Mitsek, A.I. and Semyannikov, S.S., *Fiz. Tverd. Tela*, 1969, vol. 11, p. 1103.
3. Paul, D.I., *J. Phys. C,* 1979, vol. 12, p. 585.
4. Shamsutdinov, M.A., Veselago, V.G., Farztdinov, M.M., and Ekomasov, E.G., *Fiz. Tverd. Tela,* 1990, vol. 32, p. 497.
5. Plavskii, V.V., Shamsutdinov, M.A., Ekomasov, E.G., and Davletbaev, A.G., *Fiz. Met. Metalloved.,* 1993, vol. 75, p. 26.
6. Badescu, S.C., Badescu, V., Rezlescu, N., and Badescu, R., *J. Magn. Magn Mater.*, 1999, vol. 193, p. 132.
7. Braun, O.M. and Kivshar', Yu.S., *Model' Frenkelya–Kontrovoi: Kontseptsii, metody, prilozheniya* (Frenkel–Kontrova Model: Concepts, Methods, Applications), Moscow: Fizmatlit, 2008.
8. Ekomasov, E.G., Azamatov, Sh.A., and Murtazin, R.R., *Fiz. Met. Metalloved.*, 2008, vol. 105, p. 341 [*Phys. Met. Metallogr.* (Engl. Transl.), 2003, vol. 105, no. 4, p. 313].
9. Chetkin, M.V., Kurbatova, Yu.N., Shapaeva, T.B., and Borshchegovskii, O.A., *Pis'ma Zh. Eksp. Teor. Fiz.*, 2004, vol. 79, p. 527 [*JETP Lett.* (Engl. Transl.), 2004, vol. 79, no. 9, p. 420].
10. Ekomasov, E.G. and Shabalin, M.A., *Fiz. Met. Metalloved.*, 2006, vol. 101, p. S48 [*Phys. Met. Metallogr.* (Engl. Transl.), 2006, vol. 101, suppl. issue 1, p. 48].
11. Ekomasov, E.G., Azamatov, Sh.A., and Murtazin, R.R., *Func. Mater.*, 2008, vol. 15, p. 235.
12. Farztdinov, M.M., *Spinovye volny v ferro- i antiferromagnetikakh s domennoi strukturoi* (Spine Waves in Ferro– and Antiferromagnetics with Domain Structure), Moscow: Nauka, 1988.