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MOVEMENT OF THE CIRCULAR BLOCH LINE IN A CROSS-TIE WALL IN THIN PERMALLOY FILMS

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The examination of the movement of a circular Bloch line in a cross-tie wall in permalloy films (80Ni20Fe) under the influence of two mutually orthogonal magnetic fields: H_L — parallel to the film's easy magnetization direction, and H_T — perpendicular to the easy axis. A general equation for the change in angle $\delta\varphi$, formed by a Néel segment with the easy magnetization axis, depending upon a H_L field, has been given. Two different but equally probable movements of a circular Bloch line under the influence of a H_T field (in the presence of a H_L field) have been investigated. An equation has been obtained for the magnetic field ΔH_L as a result of this movement, which together with the applied external field H_L gives a value exceeding the wall starting field ($H_L+\Delta H_L \geqslant H_S$), thus determining the creep process. A comparison of theoretical data by other authors with our own investigation results has been drawn. The conformity is fairly good.

1. Introduction

The structure of the domain wall in thin magnetic films is still the object of continuous interest regarding both purely cognitive [1, 2] and practical reasons in connection with the possibility of using the walls (cross-tie type) as information carriers in digital computers

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[3, 4]. One of the problems, which has been studied more intensively, connected with the structure of the domain walls in thin films — is the so-called wall creeping phenomenon. It consists in the motion of a domain wall under the influence of two mutually orthogonal magnetic fields: a constant one H_L parallel to the direction of easy film magnetization, and an alternating one H_T perpendicular to the easy axis. The intensity of these fields is lower than the critical starting field H_S of the domain wall. So far the phenomenon is not fully explained. In many works some attempt at explaining the wall creep mechanism has been undertaken [5–18]. The proposed models of this process do not always include the influence of basic film properties on the process, and they do not relate too clearly the creep to the parameters of external fields applied to the film. Some authors [15–18] consider the behaviour of a circular Bloch line in a cross-tie wall under the influence of external fields to be the main factor causing the creep process of this wall.

The object of our work has been the description of the movement of a circular Bloch line under the influence of: (a) a field H_L parallel to the easy axis of the film, (b) a field H_T applied along to the hard direction, (c) H_L and H_T fields acting simultaneously. In this work a constant magnetic field H_T was applied to investigate the mechanism of the creep cross-tie domain walls, because a dc magnetic field made observations of a circular Bloch line easier.

2. *A constant magnetic field H_L applied parallel to the easy magnetization direction*

For our considerations we have accepted the model of a cross-tie wall proposed by Middelhoek [19]. According to this model (Fig. 1b) the cross-tie wall consists of a 90° Néel wall (Néel segments) with an opposite magnetization, separated alternately by circular and cross Bloch lines. For cross Bloch lines, Néel wall segments can be observed; they are perpendicular to the main wall, the so-called cross-tie. In this model the angle between the magnetization vector and the easy direction near by the main wall is assumed to be 45°. By the action of a magnetic field applied along the easy direction, the magnetization vector will rotate on both sides of the main wall. At the area where the magnetization has a direction that is compatible with the turn of the external field, the angle between the M_S direction and the easy axis decreases, while on the other side of the cross-tie wall it increases (Fig. 2a). This causes, in the main wall, the rise of magnetic poles and an additional magnetic field connected with them. The poles will disappear when Néel segments take a new position, in which they will again halve the angle between the magnetization vectors in two adjacent domains (see models in Fig. 2b and c). We calculate the angle formed by Néel segments and the magnetically easy direction according to an external H_L magnetic field value. Because the angle is the same as the angle, by which the magnetization vector rotates at the area between the cross-tie, we shall use, for the calculation of this angle, the expression for free energy density for the film area near to the main wall

$$E = K \sin^2 \varphi - M_S H_L \cos \varphi - M_S H'_T \sin \varphi \tag{1}$$

where K is the uniaxial anisotropy constant, M_S — magnetization, H_L — external magnetic field parallel to the easy magnetization direction, H'_T — magnetic field resulting from

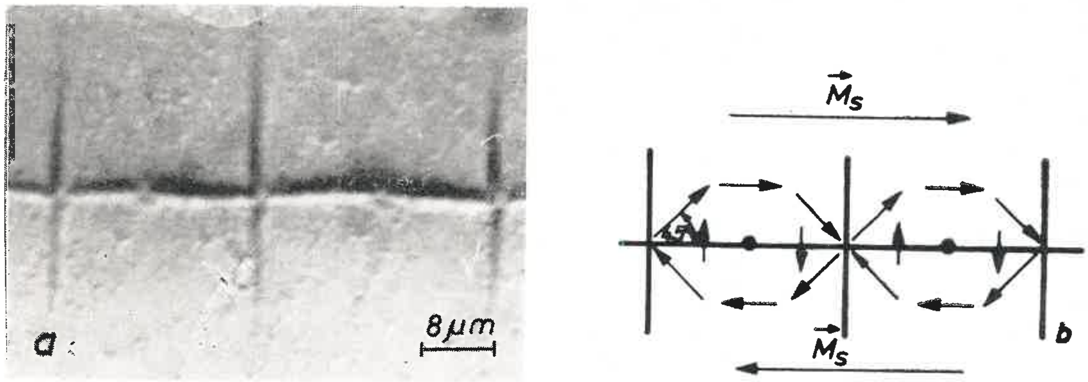

Fig. 1. Cross-tie wall in a thin 80Ni20Fe film 42 nm thick (a) and its model (b). Powder pattern method

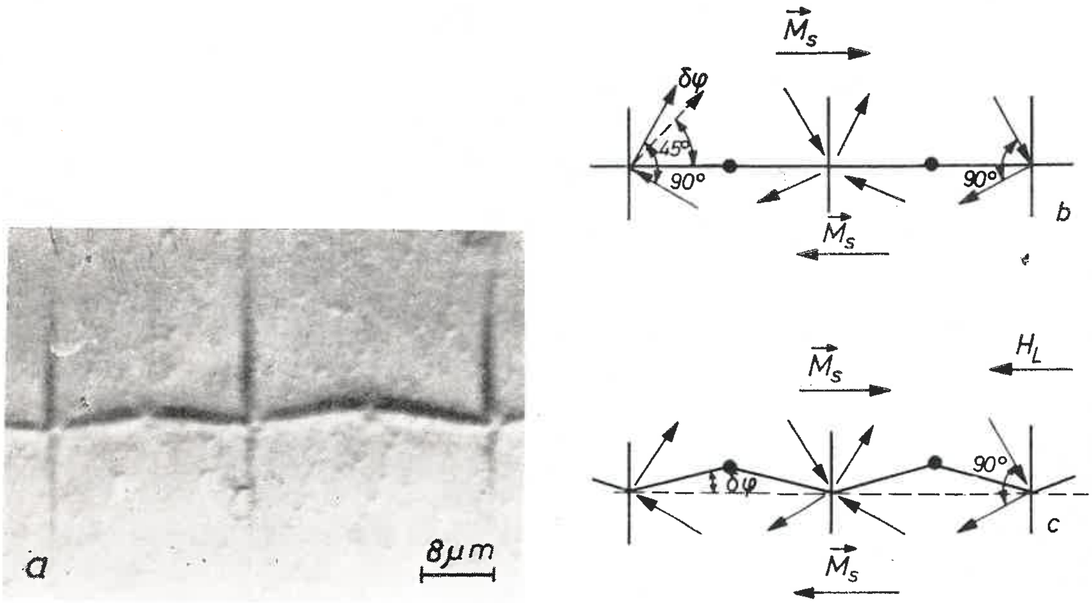

Fig. 2. Influence of an external H_L magnetic field parallel to the easy axis on a cross-tie wall structure in 80Ni20Fe film thickness 42 nm: (a) $H_L = 0.7\ H_K$, (b) scheme of rotation of magnetization vectors under the influence of a H_L field, (c) position of Néel segments in a state of equilibrium (model of a cross-tie wall presented in (a))

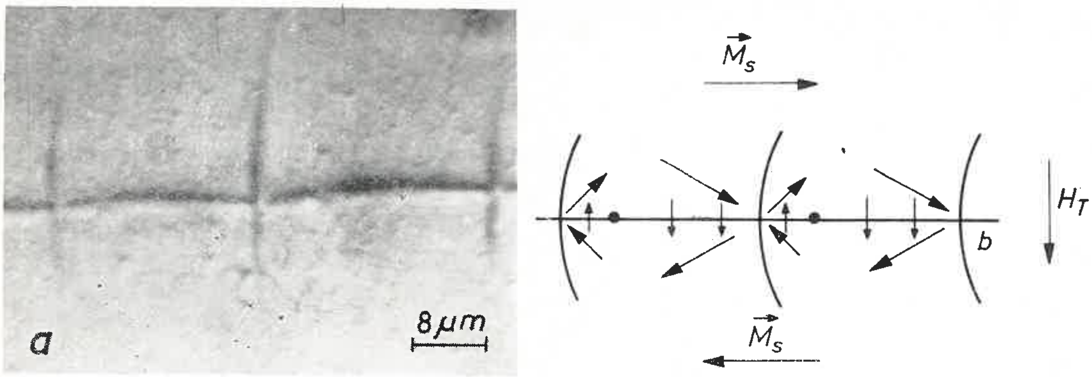

Fig. 4. Influence of a H_T magnetic field on cross-tie walls in a thin 80Ni20Fe film 42 nm thick: (a) $H_T = 0.3\,H_K$, (b) model corresponding to the cross-tie wall from (a)

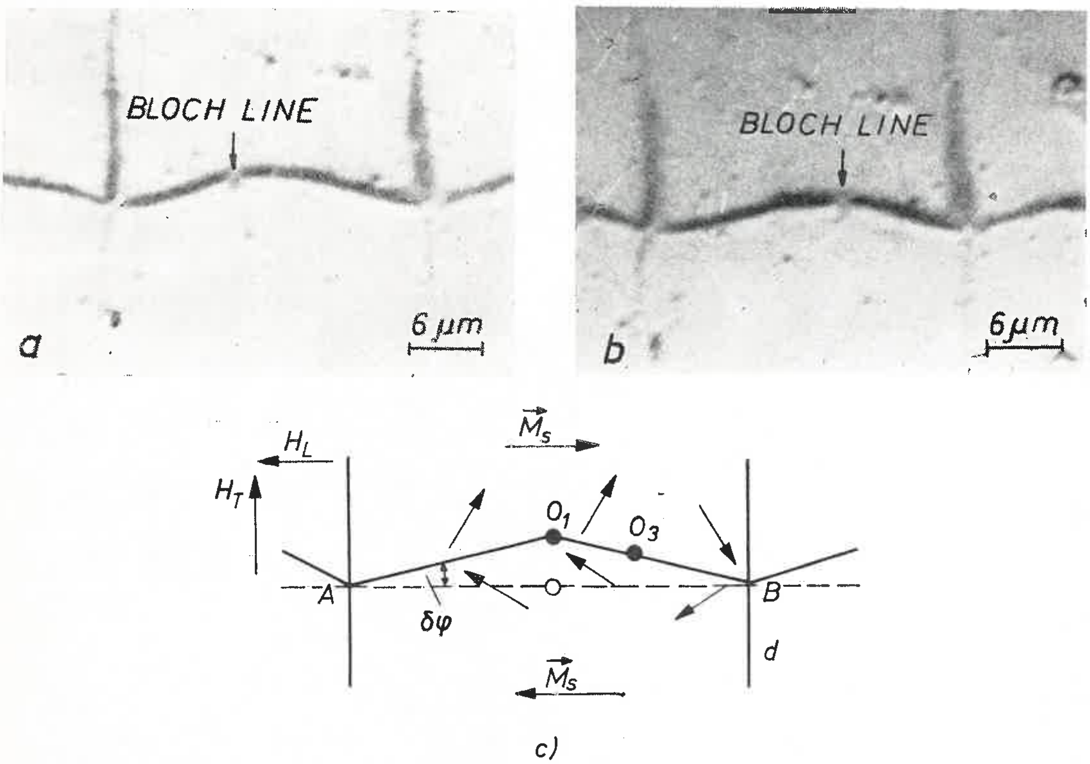

Fig. 6. Changes of a circular Bloch line position (marked with arrows) in 80Ni20Fe film 42 nm thick under the influence of the simultaneous action of H_L and H_T fields. This movement, observed by the powder pattern method is resented in Fig. a, b (in (a) — $H_T = 0.1\,H_K$, $H_L = 0.7\,H_K$; (b) — $H_T = -0.1\,H_K$, $H_L = 0.7\,H_K$), (c) — model of a cross-tie wall from (b)

the magnetic poles that produce on cross-tie wall. This magnetic field caused the deviation of the magnetization vector and the easy direction.

Introducing

$$h_L = \frac{H_L M_S}{2K} \quad \text{and} \quad h'_T = \frac{H'_T M_S}{2K},$$

equation (1) can be written down in the following form

$$E = 2K(\tfrac{1}{2}\sin^2\varphi - h_L\cos\varphi - h'_T\sin\varphi). \tag{2}$$

By minimizing equation (2) with respect to the angle φ, we get

$$\frac{\partial E}{\partial\varphi} = \sin\varphi\cos\varphi + h_L\sin\varphi - h'_T\cos\varphi \equiv 0. \tag{3}$$

In the absence of an external magnetic field ($h_L = 0$), assuming the angle $\varphi = 45°$, we get $h'_T = \frac{\sqrt{2}}{2}$, which means that the field, maintaining the magnetization vector near to the main wall line at an angle of 45° to it, is equal to $H'_T = \frac{\sqrt{2}}{2} H_K \Big($where $H_K = \frac{2K}{M_S}$,

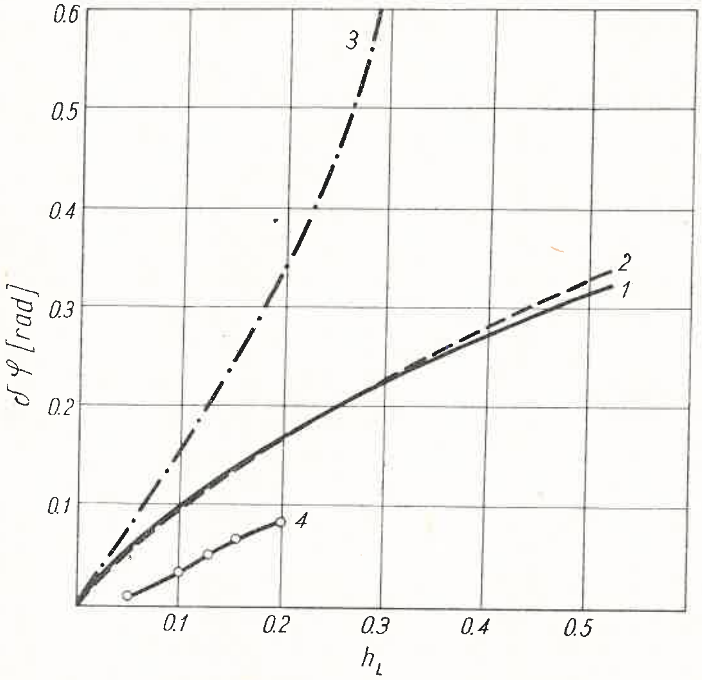

Fig. 3. Dependence of angle $\delta\varphi$ on a h_L field: curve *1* calculated to within a precision of $\leqslant 10^{-6}$ from equation (3), curve *2* calculated from equation (5), curve *3* from formula (4) from the work [18]. White circles (curve *4*) are experimental data [20], which are not measured directly but counted with deflection of the main wall (film thickness 30 nm, distance between cross-tie 40 μm)

anisotropy field$\Big)$. If the H_L field is acting on the wall along the easy magnetization direction, the above described rotation of the magnetization vector at an angle $\delta\varphi$ occurs (Fig. 2b), then Néel segments between the cross-ties bend forming the angle $\delta\varphi$ with the easy axis (Fig. 2a and model Fig. 2c). The angle $\delta\varphi$ has been calculated from equation (3), assuming that the angle $\varphi = 45°+\delta\varphi$. The iteration method has been used for the numerical solution of the equation. The accuracy of the solution for the fields h_L in the range of 0 to 0.5 was

$$|h_L \operatorname{tg} \varphi-(h_T-\sin \varphi)| \leqslant 10^{-6}. \tag{4}$$

The $\delta\varphi = f(h_L)$ values, calculated with this accuracy, are represented by curve *1* in Fig. 3. The extrapolation method has been used for the determination of the equation for the rotation angle of a magnetization vector

$$\delta\varphi = 0.785[1-e^{-h'_T(2h_L-h_L^2)}]. \tag{5}$$

The relation of the $\delta\varphi$ angle to a h_L field, calculated from the formula (5) (curve *2*) and from the equation given in the work [18] (curve *3*), has been shown in Fig. 3. From the comparison of curves it appears that equation (5) is in better accordance with curve *1*, than the formulae given in [18]. Values $\delta\varphi$ calculated from equation (5) and the expression given in [18] are higher than $\delta\varphi$ which are not measured directly but counted with deflection of the main wall in [20] (see circles in Fig. 3).

3. *A constant magnetic field H_T applied perpendicularly to the easy magnetization direction*

Under the action of a field applied perpendicularly to the easy axis a circular Bloch line is being displacement along the main wall so that the length of a Néel segment of the polarization conforming to the turn of the field increases, and Néel segment of a reverse polarization gets shortened (Fig. 4a, b). A change in magnetization direction in the area corresponding to the longer Néel segment is connected. With such an asymmetrical position of a circular Bloch line. The magnetization vector rotates reversely from the turn of the applied H_T field, and the angle between it and the easy axis decreases by a value of the sine of which is equal to the H_T/H_K ratio. Since the longer Néel segment, previously considered to be the 90° wall, turns into a wall in which magnetization performs a rotation at an angle greater than 90°, the shorter Néel segment is still considered to be the 90° wall.

4. *A simultaneous action of H_L and H_T fields*

According to the model proposed by Pogosian [18], under the influence of a H_T field in the presence of a H_L field, a circular Bloch line is displaced along line AO_1O_2 (Fig. 5), thus changing the position of a shorter Néel segment (O_2B segment), which causes the formation of magnetostatic poles on it. These poles are the cause of the appearance of a magnetic field [18]:

$$\Delta H_L = \frac{4\sqrt{2}\, M_S h_T h_a t}{a(h_a-h_T)^2}\,\delta\varphi \tag{6}$$

where h_a is the reduced annihilation field of a circular Bloch line with a cross line, t — film thickness, a — distance between circular and cross Bloch lines. Substituting $\delta\varphi$ by expression (5), we get a formula for the quantity of the magnetic field produced as a result of the above described movement of a circular Bloch line. It is considered that this magnetic

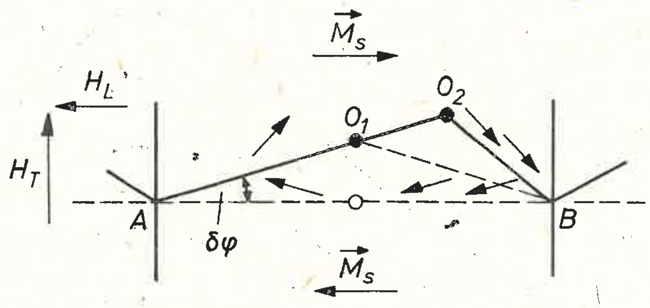

Fig. 5. Displacement of a circular Bloch line on the O_1O_2 segment under the influence of a simultaneous action of H_T and H_L fields according to [18]

field is one of the cause of the domain wall movement, since, together with the applied H field, it gives the value exceeding the wall starting field $H_L + \Delta H_L \geqslant H_S$. However, it results from our observations of domain structures carried out on thin 80Ni20Fe films at a thickness range of 30 nm to 80 nm, that the movement of a circular Bloch line under the influence of a H_T field along the O_1O_3 segment is possible (Fig. 6c), which has earlier been suggested by Torok et al. [15]. This movement, observed by means of a powder pattern method, is presented in Fig. 6a, b. Considering such a movement of a circular Bloch line to be as probable as the above described one, we can calculate the field ΔH_L of magnetostatic poles produced this time on the O_1O_3 segment. The surface density of the poles σ on this Néel wall segment depends upon the arrangement of magnetization vectors on both of its sides and equals:

$$\sigma = 2\sqrt{2}\, M_S[h_T + \cos(\arcsin h_T)]\delta\varphi.$$

Taking into consideration the fact that the distance, at which a circular Bloch line will displaced, is proportional to a H_T field [21–24], the expression for the magnetic field ΔH_L of the poles produced can be expressed by the following equation:

$$\Delta H_L = \frac{4\sqrt{2}\, M_S h_T t}{a(h_a - h_T)} [h_T + \cos(\arcsin h_T)]\delta\varphi. \tag{7}$$

Fig. 7 shows the dependences of ΔH_L fields upon film thicknesses (t), which are calculated from the formulae (6) and (7) respectively, and from the equation of Pogosian [18]. For comparison, based upon the data from [21], an experimental curve (curve *1*) has also been given. The experimental data as well as calculations concern 80Ni20Fe films, for which $M_S = 6.4 \times 10^4$ A/m, and the annihilation field of a circular Bloch line with a cross line at the investigated film thickness range is 0.5 H_K. The field ΔH_L has been calculated from the equation of domain wall starting field $H_S = H_L + \Delta H_L$, substituting H_L and H_S

from the experimental measurements of a thin permalloy film. The magnetic field H_L corresponds to such a value of the acting field in the easy direction, which causes in the presence of the H_T field, for the first time an irreversible change in the position of the

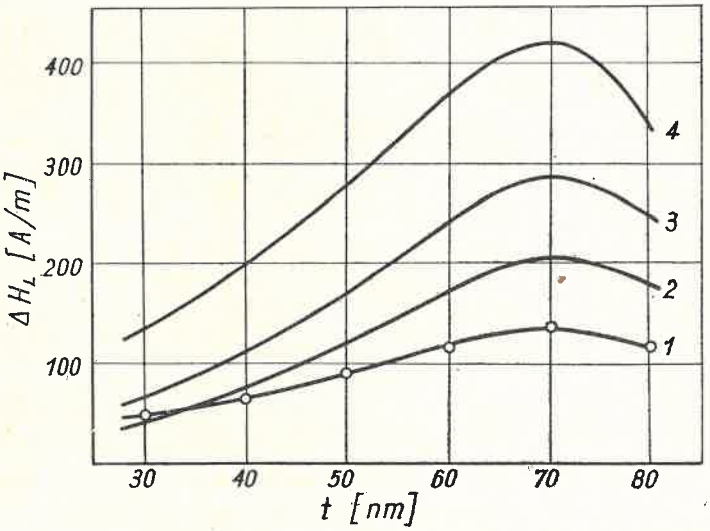

Fig. 7. Dependence of ΔH_L fields on film thickness t: curve *1*— experimental data, curve *2* and *3* calculated from formulae (7) and (6) respectively, curve *4* from a formula from the work [18]

domain wall. The calculation of the ΔH_L field was carried out to within an accuracy of ± 4 A/m. The film thickness was measured to within an accuracy of ± 20 Å. The remaining data, used in calculations, are given in Table I.

TABLE I

Film thickness t [nm]	Distance between cross-tie $\bar{\lambda}$ [μm]	Starting field H_S[A/m]	Anisotropy field H_K[A/m]	Magnetic field H_L for $H_T = 0.2H_K$
30	35	160	300	68
40	24	154	310	57
50	12	151	320	40
60	9	145	330	30
70	7	150	345	25
80	6	145	330	14.2
90	14	140	330	19.5

5. *Conclusions*

It results from the comparison of curves presented in Fig. 7 that the curve plotted on the basis of the model proposed by Pogosian [18] shows the greatest discrepancy from the experimental data. It is especially connected with another way of determining the angle $\delta\varphi$. A better conformity of curve 2 (Fig. 7) with the experiment in comparison with curve *3* and *4* shows the movement of a circular Bloch line along the Néel segment (O_1A segment in Fig. 6c) to be supposedly more probable than the movement investigated by Pogosian [18].

The model of a creep phenomenon that has been proposed in the present work takes into account the influence of the essential parameters, denoting film properties, on this process. Among other things, this model describes very well the experimental fact of the change of creep field threshold values with the change of film thickness (this field decreases at the film thickness range from 30 nm to 70 nm, while above this thickness it increases). Basing on the said model, one can estimate the magnitudes of the applied external magnetic fields causing the creep phenomena.

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