On the Maze-like Domain Structure

著者	FUJIMURA Takashi
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On the Maze-like Domain Structure*

Takashi FUJIMURA

The Research Institute for Iron, Steel and Other Metals

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Synopsis

The structure of closure domains bounded by zigzag shaped boundaries is investigated. Present theory explains well the general feature of the zigzag boundaries between maze-like domains observed by Chikazumi et al. The degree of zigzag depends on the magnitude of internal stress in the surface layer of the crystal. From the relation between zigzag angle and the internal stress, the magnitude of internal stress in the vicinity of the scratch drawn on the crystal surface is estimated.

I. Introduction

Very fine maze-like domain patterns are usually observed on the topmost surface of a ferromagnetic crystal which has been mechanically polished(1). But, when the surface layer is removed by electrolytic polishing, these patterns vanish and there appears a simple domain pattern which corresponds to the inner domain structure(2). Then, it seems to be certain that the maze pattern is only observed on the surface where strong internal stress prevails. However, the influence of intenral stress on the maze domain structure has not been satisfactorily explained.

Recently, by a careful observation on the large maze domain which appeared along the strong scratch drawn on (100) plane of the Fe-Si single crystal, Chikazumi et al.(3) found that the boundary between the maze domains was zigzag shaped and the direction of magnetization in the domain bounded by a zigzag line was antiparallel each other and perpendicular to the direction of the zigzag line. An example of the maze-like domain pattern observed by them is schematically shown in Fig. 1. As shown in the figure, degree of zigzag, amplitude and wave length of zigzag curve vary with the distance from the scratch. In order to explain these several characters of zigzag boundary, we will study the influence of internal stress on the maze-like domain pattern.

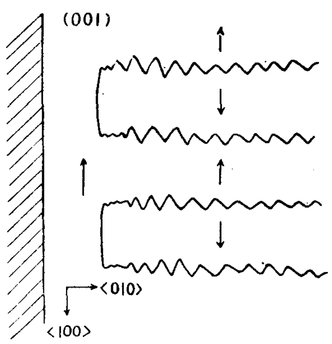

Fig. 1. Schematic representation of zigzag boundaries.

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(2) H.J. Williams, K. E. Bozorth, and W. Schockley, Phys. Rev., **75** (1949) 155.
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II. Zigzag shaped domain boundary

In a cubic ferromagnetic crystal with [100] easy direction, the 180° -wall between a [100] domain and a [$\bar{1}$00] domain should be the plane parallel to [100] direction and the 90° -wall between a [010] domain and a [001] domain should be the plane parallel to [011] direction, because normal component of magnetization is always continuous across these walls. Then, if a closure domain in the surface layer of the crystal is bounded by the plane parallel to [011] direction, the domain boundary on the (100) plane is parallel to [100] direction, only when the wall of the closure domain is parallel to (011) plane and otherwise, the domain boundary should be oblique to [100] direction.

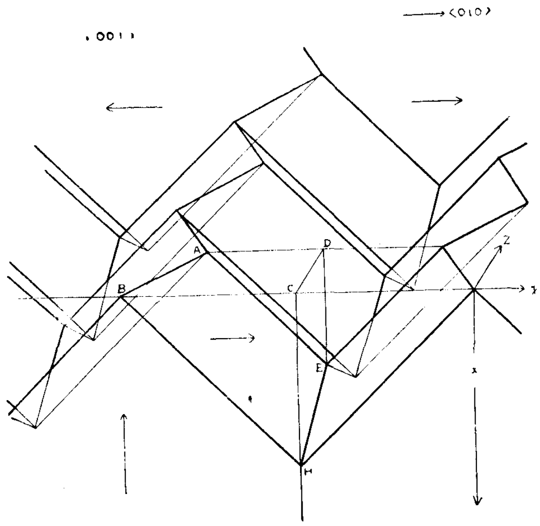

Fig. 2. Structure of zigzag wall.

The domain structure shown in Fig. 2 is a scheme of a closure domain separated by the zigzag domain wall. But, this domain structure should be somewhat changed by the following reason: Stress component π_{zz} is compressive and π_{xx} is only positive and favor the X-domain and disfavor the Y-domain. Therefore, in order to reduce magnetoelastic energy in the closure domain, the domain structure, above-mentioned, should be changed to the one as shown in Fig. 3. In

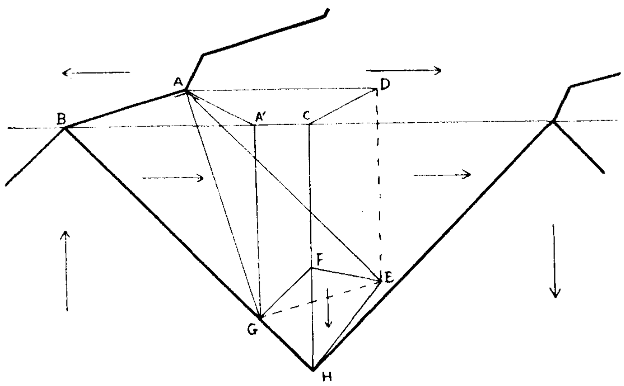

Fig. 3. Model of zigzag wall applied to calculation.

Fig. 3, the zigzag boundary on the (001) plane is designated by AB and the domain wall is the area ABGEF and closure domain is the volume ABCDEFG. The normal component of magnetization is continuous across both boundaries, ABGE and EFG. Since magnetoelastic energy in the closure domain is reduced by an amount contained in the volume EFGH, while total amount of wall area does not change, the domain structure shown in Fig. 3 should be more favorable in comparison with the one shown in Fig. 2.

Now, AA' is the intersecting line of the (001) plane and the plane which is perpendicular to both (001) and the wall planes. We denote, $CD=L$, $AD=D$, $\angle A'AD=\gamma$, $\angle A'AG=\alpha$. The relation between α and γ is given by,

$$\tan\alpha = \sec\gamma\,. \tag{1}$$

The area of the wall, S, and the volume of the closure domain, V, are given by the following equations, respectively.

$$S = \frac{LD'}{2}\sec\alpha\,, \tag{2}$$

$$V = \frac{LD'}{2}\left\{1-\frac{7}{3}\left(\frac{\sin^2\gamma}{2+\sin^2\gamma}\right)^2\right\}, \tag{3}$$

where $D+L/2\tan\gamma$ is denoted by D'.

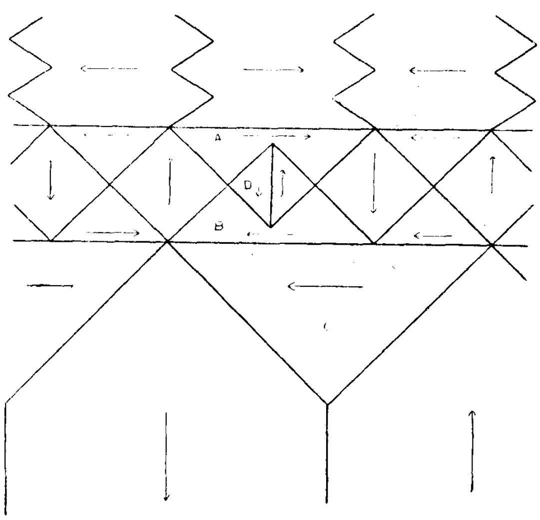

Fig. 4. Section of zigzag wall. (Underlying domain)

Nextly, we will call our attention to the underlying domain structure which should have an intimate relation with the closure domain structure. Various kinds of underlying domain structure can be speculated, however, a typical one shown in Fig. 4 is considered now. In this case, magnetic flux closes in the closure domains, (A) and (B), in the surface layer and in the underlying domain, (C), respectively. Total energy per unit area of the crystal surface, E, is given by,

$$E = (2+\sqrt{2})\,\sigma\sec\alpha+\sigma_0\frac{\sin^2\gamma}{2+\sin^2\gamma}+\frac{\sigma_0}{2}\left(1+\frac{P}{2D'}\right)$$

$$+\frac{D'}{2}(W_1+W_2)\left\{1-\frac{7}{3}\left(\frac{\sin^2\gamma}{2+\sin^2\gamma}\right)^2\right\}+W_3D', \qquad (4)$$

where, σ_o and σ are the wall energy of 180°- and 90°- wall per unit area, respectively, and W_1, W_2 and W_3 are the amount of magnetoelastic energy density in the domain (A), (B) and (C), respectively. P is the depth of the underlying domain.

The total energy is minimized by the condition,

$$\frac{\partial E}{\partial D'}=0,$$

which gives the stable width,

$$D'=\left\{\frac{P\sigma_0}{2(W_1+W_2)\left\{1-\frac{7}{3}\left(\frac{\sin^2\gamma}{2+\sin^2\gamma}\right)^2\right\}+4W_3}\right\}^{1/2}. \qquad (5)$$

In this expression, the second term in Eq. (4) is neglected, since it is fairly smaller than the other terms.

In regard to the magnetoelastic energy density in each domain, we assume that it decays stepwise towards interior from the crystal surface. Then, for the following cases, Eqs. (4) and (5) are changed to,

(1) $W_1 : W_2 : W_3 = 1 : \frac{1}{2} : \frac{1}{4}$

$$E_1=(2+\sqrt{2})\sigma\sec\alpha+D'W\left\{1-\frac{7}{8}\left(\frac{\sin^2\gamma}{2+\sin^2\gamma}\right)^2\right\}+\frac{\sigma_0}{2}\left(1+\frac{P}{2D'}\right), \qquad (6)$$

$$D_1'=\left[\frac{P\sigma_0}{W_1\left\{5-\frac{7}{2}\left(\frac{\sin^2\gamma}{2+\sin^2\gamma}\right)^2\right\}}\right]^{1/2}. \qquad (7)$$

(2) $W_1 : W_2 : W_3 = 1 : \frac{1}{4} : \frac{1}{8}$

$$E_2=(2+\sqrt{2})\sigma\sec\alpha+D'W\left\{\frac{3}{4}-\frac{35}{48}\left(\frac{\sin^2\gamma}{2+\sin^2\gamma}\right)^2\right\}+\frac{\sigma_0}{2}\left(1+\frac{P}{2D'}\right), \qquad (8)$$

$$D_2'=\left[\frac{P\sigma_0}{W_1\left\{3-\frac{35}{12}\left(\frac{\sin^2\gamma}{2+\sin^2\gamma}\right)^2\right\}}\right]^{1/2}. \qquad (9)$$

III. Comparison with experiment and discussion

The variation of total energy can be given by the following expression as a function of γ,

$$\left.\begin{aligned}E&=\left[\sigma\sec\alpha-Z\left(\frac{\sin^2\gamma}{2+\sin^2\gamma}\right)^2\right]+\text{const.},\\ \tan\alpha&=\sec\gamma,\end{aligned}\right\} \qquad (10)$$

where

$$\left.\begin{aligned}Z&=\frac{21}{(2+\sqrt{2})16}\lambda\bar{\pi}_{xx}D', \quad \text{for case (1)}\\ Z&=\frac{105}{(2+\sqrt{2})96}\lambda\bar{\pi}_{xx}D', \quad \text{for case (2)}\end{aligned}\right\} \qquad (11)$$

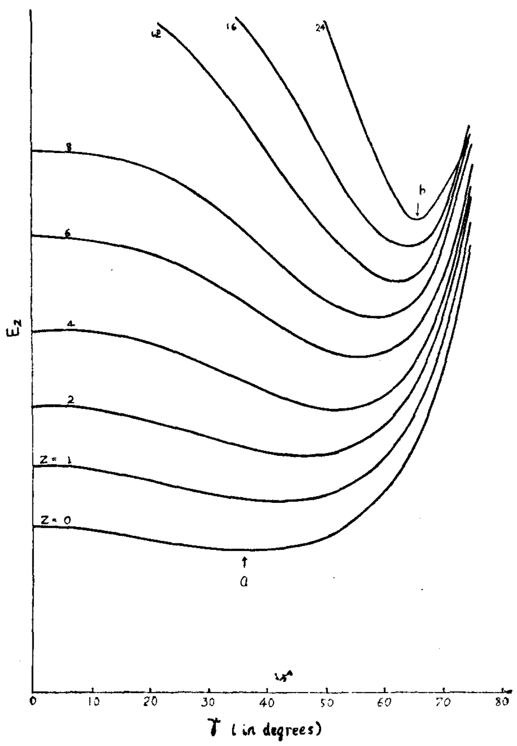

Fig. 5 E-γ curves.

λ is a constant of magnetostriction and $\bar{\pi}_{xx}$ is the mean value of π_{xx}.

In the calculation of E, it must be noticed that the surface energy of the 90°-wall varies with the change of azimuthal range in which spin rotates in the wall plane(3). That is, the wall of least energy is parallel to a (100) plane and the energy increases with the rotation of the plane towards (100)→(111)→(011). Accordingly, taking account of variation of the surface energy σ with the rotation of the wall plane, the first term of Eq. (10) is calculated. The curves of E vs γ for several values of Z are shown in Fig. 5. As can be seen in the figure, γ_c, the value of γ corresponding to the minimum of E, increases with the amount of Z. So that, zigzag angle w, which is given by $2(\pi-\gamma_c)$, monotonously decreases with the amount of internal stress, since Z is proportional to the internal stress.

The relation between wave length of the zigzag boundary and the width of the closure domain is given by,

$$\frac{L}{D'}=\frac{\sin 2\gamma}{2+\sin^2\gamma}.$$

L/D' becomes maximum when γ is approximately 40° and tends to zero when γ becomes smaller or larger than this critical value. Now, as shown in Fig. 1, the width of a maze-like domain does not change in some reach on which zigzag angle of the boundary varies appreciably with the distance from the scratch and then, if the width of the closure domain is assumed to be invariant, the wave length becomes extremely small as the value of γ approaches to 90°. This matter is consistent with the experimental evidence shown in Fig. 1.

As mentioned above, the relation between the zigzag angle and the amount of internal stress has been obtained and then, if w is measured at any place in the vicinity of the scratch, then the amount of internal stress at that place can be estimated by Eq. (11). By taking $\lambda=2.5\cdot 10^{-5}$cm/cm and $D'=2\cdot 10^{-3}$cm (half width of the maze-like domain observed by Chikazumi et al.), the amount and the distribution of internal stress in the vicinity of the scratch are calculated. As shown in Fig. 6, internal stress decreases monotonously with the distance from the scratch.

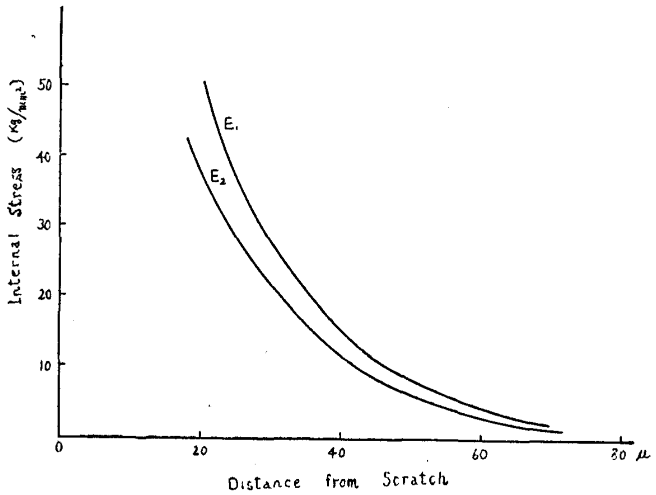

Fig. 6. Distribution curves of internal stress.

The depth of the underlying domain, P, which varies with the distance from the scratch, can be estimated by Eq. (9). The values of P are about 10^{-1}cm at the distance of 20 microns and 10^{-2} cm at 100 microns, respectively. Therefore, the depth of the underlying domain in the vicinity of the scratch is tenfolds of that in the region where internal stress vanished. This conclusion is consistent with the experimental fact that the surface layer is deeply strained near the scratch.

If magnetic flux closes in the closure domain structure of the surface layer, the underlying domain structure is almost independent of the surface domain structure. Then, in general, D' can be given by,

$$D' = \left\{ \frac{P\sigma_0}{\left[2(W_1+W_2)\left\{1-\frac{7}{3}\left(\frac{\sin^2\gamma}{2+\sin^2\gamma}\right)^2\right\}+4mW_3\right]m} \right\}^{1/2}$$

where m is integer. (Fig. 4 is the case where m equals to 1). As a extreme case, for large vaule of m, D' can be given by,

$$D' \fallingdotseq \frac{1}{2m}\left(\frac{P\sigma_0}{W_3}\right)^{1/2}.$$

If P=2 mm and the magnitude of internal stress in (C) domain is 1 Kg/mm², then $2mD'$ is 0.2 mm; this value is the same order of magnitude of a magnetic domain width observed on the electrolytically polished surface.

An alternative domain structure is shown in Fig. 7. In this case, magnetic poles appear on the surface of (E) domain and magnetostatic energy in the (E) domain should increase with the zigzagness of the closure domain boundary. But, it is difficult to decide whether a general case of Fig. 4 or the case of Fig. 7 is appropriate to lower the total energy of the maze domain structure, because at present, distribution of internal stress and magnetostatic energy in the (E) domain are not accurately estimated.

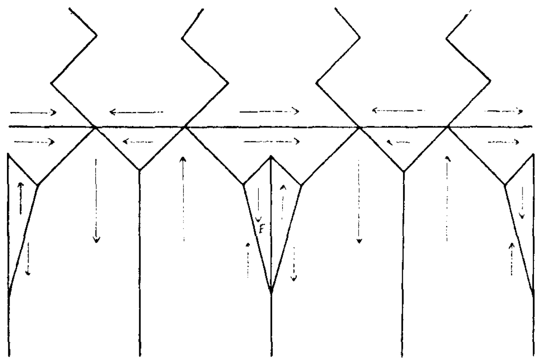

Fig. 7. Another model of zigzag wall.

The variation of zigzag angle has been explained by Chikazumi et al., basing on the other view point. They emphasized that the normal component of magnetization in the closure domain is not continuous across the wall and there appear free poles on it and zigzag angle is influenced by the appearance of these free poles, since the internal stress π_{xx} may favor the underlying domain and disfavor the closure domain, it makes the depth of the latter smaller. Using the relation between intensity of free pole and the magnitude of internal stress, they estimated the magnitude of internal stress from the zigzag angle and found the amount of internal stress as the order of 100 kg/mm^2 at the distance of 0.02 mm from the scratch. This value is two times as large as the value estimated by us.

In conclusion, it should be remarked that the existence of (D) domain in the surface layer is favorable to lower the total energy of the maze-like domain structure, however, there is no experimental evidence of this domain structure, for domain pattern is usually observed only on the topmost surface of the crystal. And hence, it is not clear whether the domain such as (D) is surely existing under the surface of the crystal or not.

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