Mutual transformations and annihilation of the microstructural elements in 180-degree domain wall of iron

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Mutual transformations of the point substructural elements in the near-surface region of 180-degree domain wall of iron, namely of the Bloch point and ot two types of emergence of vertical Bloch lines to a surface, which occur as a result of their approaching and subsequent merging in external magnetic fields, were investigated and systematized. In the external field, perpendicular to the plane of the wall and exceeding the critical value (about 400 Oe), the near-surface region of the crystal becomes magnetized; the near-surface region of the wall with the structure of the type of horizontal Néel line is a nucleus of a new phase.

1. INTRODUCTION

The emergence of an 180-degree domain wall (DW) to the surface of a massive ferromagnet is a one-dimensional micromagnetic formation.[1,2] The observed structure corresponds to the model of the Hubert[3] asymmetrical Bloch wall, in which the Bloch structure in the crystal's volume changes to the Néel structure in the near-surface region via asymmetrical bending of DW (Fig. 1). In such a one-dimensional formation of the type of a horizontal Néel line (HNL), three types of point structural elements, which divide it into subdomains, are possible: emergences of two types of vertical Bloch lines (VBL) to the surface and a singularity of the type of a Bloch point (BP).[2] Figure 1 shows all three types of point formations. The VBL emergences to the surface are such that in one case the signs of the Néel magnetization components are different on different sides of VBL and the directions of DW bending are identical (VBL-1). In the other case, the signs of the Néel component are identical but the bending directions are different, which causes a shift of the near-surface region of the wall by approximately $0.4\,\mu$m (VBL-2). The same shift occurs in a BP region, where both the sign of the Néel magnetization component and the direction of the bending change with DW polarity remaining unchanged in the volume.

The displacements of BP and VBL in constant magnetic fields were investigated in Ref. 4. The authors of the present paper studied the processes of convergence of BP, VBL-1, and VBL-2 in iron monocrystals in a magnetic field and observed their mutual transformations and annihilation as a result of merging.

2. SAMPLES AND EXPERIMENTAL PROCEDURE

Filamentary iron monocrystals, obtained by hydrogen reduction of iron halide salts, served as samples. Square samples with the side $d = 30$–$150\,\mu$m and length $L = 2$–10 mm, with natural optically perfect (100) faces, were selected for measurements. The investigations have been undertaken on the samples containing one 180-degree DW, centrally located along the crystal axis and which could be interrupted by square domains in which the magnetization is perpendicular to the crystal axis and which are bounded by 90-degree DW (see Fig. 1). The domain structure was visualized with the help of the meridional Kerr effect (KE) in the apparatus assembled on the basis of MBS-10 microscope.

Filamentary iron monocrystals have a perfect crystalline structure.[5] For our samples this was confirmed by a magnetooptical investigation of DW vibrations by the procedure[4] that has shown that the coercive field of a DW in crystals does not exceed several thousandths of an oersted.

A substructure of the near-surface region of the wall has been investigated with the help of magnetooptical micromagnetometer,[2] employing the Kerr magnetooptical effect (KME), by determining the direction of bending and the sign of the Néel magnetization component of the DW upon shifting along the wall. Since the magnetooptical effect, determined by magnetization in DW, is very small, the measurements were carried out in the presence of DW vibrations arising under the action of an alternating field H_y, which made it possible to measure the effect by phase detection, which is considerably more sensitive than the static method. The amplitude of DW vibrations (Δ_{DW}) was selected close to the effective width of 180-degree DW in the volume of iron crystals (δ), which is 0.2 μm. In this case, during the scanning of the detector window across the vibrating DW we observe alternating KME curves determined by the Néel magnetization component in DW. The sequence of the prin-
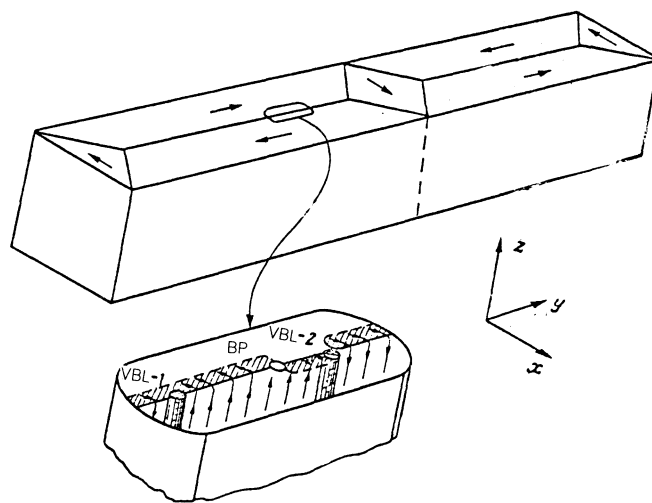

FIG. 1. Domain structure of a filamentary iron single crystal. A fragment of 180-degree DW and possible point substructural elements in the wall's near-surface region are shown on the insert.

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cipal positive and negative extrema is determined by the sign of the Néel component, while the direction of the bending is determined by the position of the small extremum with respect to the two principal extrema. The details of the investigation procedure of DW structure can be learned from (2).

Magnetic fields in three mutually perpendicular directions, necessary for solving the problems formulated in the paper, were created with the help of Helmholtz coils. The fields created by the coils reached several hundred oersteds. An electromagnet with a magnetic core was used to create a field $H_x \gtrsim 1$ kOe. BP and VBL shifting is observed under the action of the fields H_x and H_z, respectively. If there are DW vibrations with the amplitude $\Delta_{DW} \sim \delta$, the activation condition for BP and VBL shifts in the fields H_x and H_z is realized, under which coercitivity of BP and VBL is completely suppressed and their displacements in outer fields are reversible.[4] Exact orientation of the fields H_x and H_z relative to the crystal axes (see Fig. 1) was made with the help of the aligning table on which the sample was fastened. The orientation of the fields relative to the crystal's longitudinal axis was checked by measuring the KME determined by magnetization in the domains. The accuracy of adjusting the fields H_x and H_z perpendicular to the magnetization direction in the domains was in the range of several thousandths of a degree.

3. EXPERIMENT

The near-surface substructure of 180-degree DW is periodic by its nature. Usually areas of the type VBL-BP-VBL-BP are observed.[4] Their sequence may be interrupted by the areas of the VBL-VBL type. Sometimes groups of several BP, located between a pair of VBL, were found. This made it possible to investigate the convergence of BP pairs in the outer field. In the field H_x the degeneracy of the energy of the near-surface HNL with respect to the sign of the Néel magnetization component is lifted (see Fig. 1, and also Fig. 3a). This leads to a displacement of BP and an increase in the subdomain in which the signs of the Néel component and the field H_x coincide. Curve 1 in Fig. 2 describes the convergence and annihilation for two BP with increase of H_x, which was observed for the first time in (4). With an increase of H_x, both BP move towards each other. Figure 3a illustrates this process. The distance T between BP (in the
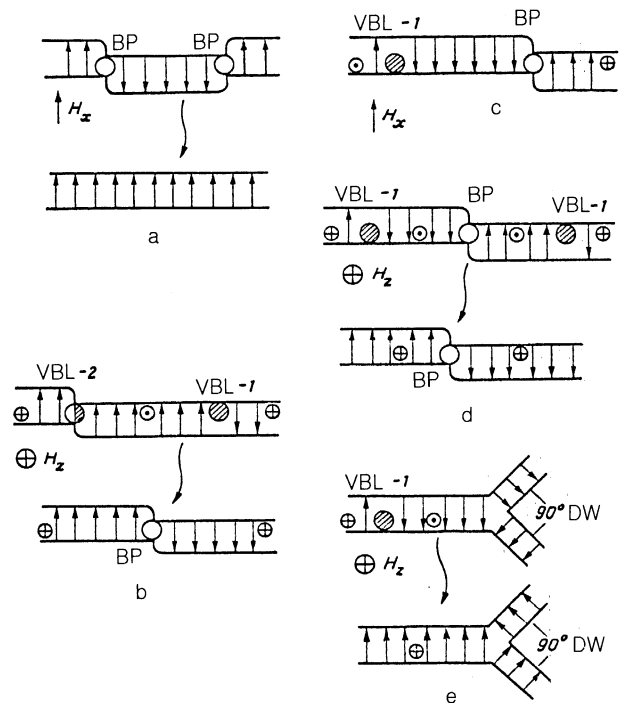
FIG. 3. Processes of mutual transformations and annihilation of two(a, b) and three (d) low-dimensional structural elements in 180-degree DW in the fields of different orientation: c—a special case—BP and VBL do not merge for any values of the field H_x (for details see the text); e—absorption of VBL by the line of intersection of 180-degree and two 90-degree DW in the field H_z. Symbols ⊙, ⊕ show the position of the wall in the crystal's volume and the direction of magnetization in the wall.

absence of field was 30 μm. The value of T depends on the field practically linearly up to the values of $H_x \approx 60$ Oe and in this case decreases to $T \sim 5 \mu$m. Then the approach velocity of the points decreases and in the field $H_x \approx 170$ Oe they annihilate.

Similar to the case of the Néel component of DW in the field H_x, in the field H_z degeneracy lifting of the energy of the DW adjacent subdomains takes place in the volume. This results in a VBL shift and, consequently, in the growth of some subdomains and the decrease of others. Curve 2 in Fig. 2 describes the convergence process for VBL-1 and VBL-2 in the field H_z, which in this case move towards each other. For $H_z = 0$ the distance between them was 33 μm and then it was diminishing practically linearly with the growth of the field up to $H_z \approx 100$ Oe. With the further growth of the field the slope of the curve $T(H_z)$ diminished. In a 200 Oe field the distance between VBL was 2 μm and at $H_z \approx 215$ Oe they annihilated, as a result of which a BP has been formed. This process is illustrated by Fig. 3b. Measurements have shown that the $T(H_z)$ dependences and the values of annihilation fields practically coincide for the pairs VBL-1 and VBL-1, VBL-1 and VBL-2, and VBL-2 and VBL-2.

The convergence process for VBL-1 and BP in the field H_x is described by curve 3 in Fig. 2, and here only BP moves, while VBL in this case remains fixed. The distance between them changes linearly from $T = 40$ to $T = 10 \mu$m with an increase in the field from zero to 50–60 Oe. With the field growth the convergence continues up to the distance between them $T \sim 1 \mu$m at $H_x \sim 400$ Oe. With the further field growth an abrupt phase transition occurs in the sample, as a
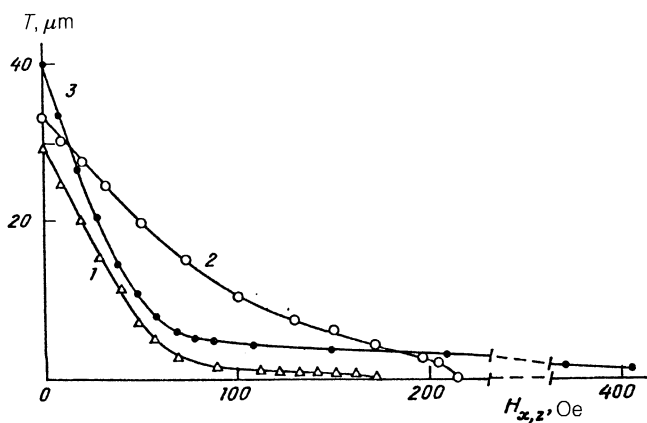

FIG. 2. Convergence and annihilation (curves 1 and 2) of low-dimensional structural elements of 180-degree DW in outer magnetic fields for the crystal with $d = 50 \mu$m: 1—two BP in the field H_x, 2—two VBL (VBL-1 and VBL-2) in the field H_z, 3—BP and VBL-1 in the field H_x.

result of which the near-surface region of the crystal becomes rearranged: separate areas of the surface become magnetized in the direction of H_x. Visual investigation made with the help of MKE has shown that the surface areas magnetized along the x axis are arranged periodically on opposite sides of 180-degree DW. Obviously, when a crystal is magnetized in the direction of the x axis, the intervals of the DW near-surface region in which the sign of the Néel magnetization component coincides with the field's sign, serve as magnetic reversal centers of the crystal's near-surface region. Hartmann and Mende[6] observed an abrupt magnetization of the near-surface region of filamentary iron crystals along the x axis in the case when 180-degree DW approached the crystal's edge under the action of the field H_y. The periodic arrangement of the crystal's near-surface regions, magnetized along the x axis, can be associated with the periodicity of the DW near-surface structure, observed in (4).

The curves which describe the convergence of two BP and also BP and VBL, including VBL-1 and VBL-2, in the fields $H_x > 60$ Oe, are practically identical for the substructural elements located at different distances from each other at $H_x = 0$ in the same crystal, as well as in different crystals.

Possible transformations of the pairs of the DW substructure elements during their convergence in the outer field are shown in Table I. The absence of substructural peculiarities in DW is denoted by zeros. All the transformations given in the table were observed in the experiment except for those marked with asterisks. It might be expected the asterisked transformations would be realized in the field H_x, however, as noted, a rearrangement of the crystal's near-surface structure takes place before the indicated substructural elements merge.

Still more complex mutual transformations have been observed. For example, Fig. 3d illustrates the annihilation of three elements, two VBL-1 and BP between them, in the field H_z, which results in the formation of a point with a structure different from that of the original BP. The presence of BP between two VBL practically has no effect on the process of their convergence and the value of the annihilation field. Using the table, one can predict the result of mutual transformations upon the approach of not only two, but also three and more structural elements. To this end it is necessary to consider the transformations successively, grouping the elements into pairs and determining the transformation result for each pair of elements from the table.

Figure 3e illustrates the convergence of VBL and the line of intersection between 180-degree and two 90-degree walls. In this case VBL is absorbed by the stationary line of intersection of the walls in the field $H_z \approx 160$ Oe.

4. DISCUSSION

The initial linear sections of the curves $1, 2$, and 3 in Fig. 2 are due to a long-range magnetostatic interaction in the crystal. Separating DW into subdomains decreases the magnetostatic energy. A decrease in the slope of curve 2 in Fig. 2 for $H_z > 100$ Oe obviously results from the fact that upon the VBL convergence the role of nonlinear terms in the relation between the magnetostatic energy and $T_{\text{VBL-VBL}}$ increases and the exchange interaction between the lines begins to affect their convergence. Approximating the initial section of curve 2 to the intersection with the x axis makes it possible to

TABLE I. Transformations of substructural elements in the near-surface region of 180-degree DW.

	VBL-1	VBL-2	BP
VBL-1	0	BP	VBL-2*
VBL-2	BP	0	VBL-1*
BP	VBL-2*	VBL-1*	0

estimate the value of the field of DW magnetization to saturation, which amounts to 130 Oe. The value of a similar field, measured by Hartmann and Mende with the help of Bitter's method for a filamentary crystal with $d = 30$ μm, was 160 Oe (for the case of DW magnetization under activation condition).[7] This agrees with our results for a crystal with $d = 50$ μm, since[7] the DW susceptibility increases linearly with d.

A remark is in order now. Hartmann and Mende assumed that the DW normal magnetization component on the crystal's surface (M_{DW}^n) reaches its maximum value M_s. According to our measurements,[2] the value of M_{DW}^n does not exceed $0.1 M_s$. The correct estimate of the DW thickness in the volume (δ), obtained under a false assumption on the value of M_{DW}^n,[7] can be explained by the fact that, owing to demagnetization effects, the outer field H_z becomes reduced inside the crystal approximately to the same degree. The degree of field reduction (α) is determined by the expression $\alpha = 2\pi M_s / H_k$, where M_s is the saturation magnetization, $H_k = 2K_1 / M_s$ is the anisotropy field, and K_1 is the cubic anisotropy constant. For iron $K_1 = 4.6 \cdot 10^5$ erg/cm^3, $4\pi M_s = 2.1 \cdot 10^4$ G (Ref. 8), whence $\alpha \approx 20$. Neglect of the weakening of the field H_z in the crystal volume and the overestimate of M_{DW}^n canceled each other and, as a result, the authors[7] have obtained a correct estimate of the value of δ.

Absorption of a VBL by the line of intersection of 180-degree and two 90-degree DW in the field $H_z = 160$ Oe, which is less than the annihilation field of two VBL in the same crystal ($d = 50$ μm), shows, evidently, that the interaction between VBL and the indicated line is less than between two VBL.

Curves 1 and 3 in Fig. 2 depict the magnetization of the near-surface HNL, a one-dimensional object, in the field H_x, similar to magnetization of a two-dimensional object, DW, in the field H_z, and a three-dimensional object, the crystal itself, in the field H_y. A decrease in the slope of curves 1 and 3 begins in the fields $H_x = 50$–60 Oe and is caused apparently by the same reasons as in the case of curve 2, i.e., by a nonlinear dependence of the magnetostatic energy on $T_{\text{BP-BP}}$ and $T_{\text{VBL-BP}}$, respectively, and the effect of the exchange interaction upon convergence of substructural elements. Nonlinear dependence $T(H_x)$ for VBL and BP appears when the distance between them becomes twice as long as between two BP, and the lower limit of the field of VBL and BP merging (400 Oe) exceeds more than twice the annihilation field of two BP (170 Oe, see Sec. 3).

Note that in the case of two VBL their convergence in the field H_z is determined by a nonlocal magnetostatic energy (in the sense of Malozemoff and Slonczewski[9]), which is due to the presence of the normal magnetization constant at the emergence of the DW subdomains to the crystal's surface (and, consequently, to the presence of σ-charges in the

sense[9]). In the cases of BP and VBL and two BP the convergence is determined by a local magnetostatic energy caused by π-charges. The π-charges are associated with the presence of a magnetization x-component in the near-surface region of DW.

A HNL subdomain, located between two BP (Fig. 3a), is compressed due to the pressure exerted on it in the field H_x by the neighboring subdomains. Following the analogy suggested in Ref. 9 for a pair of VBL, in our case an interval of HNL with a pair of BP can be compared to a rubber band with fixed end points and twisted in the middle by 180°.

The qualitative difference between curves *1* and *3* in Fig. 2 can be explained by the fact that for a BP-BP pair an HNL segment in the field H_x undergoes pressure on both sides, while for a pair of BP-VBL only on one side, on the side of BP. The absence of pressure on the side of VBL on the HNL interval between VBL and BP is due to the fact that VBL is stationary in the field, while the position of the near-surface region of VBL is stabilized by its volume part.

5. CONCLUSION

The processes of converging and merging of different pairs of substructural elements in the near-surface region of 180-degree DW in iron (BP, VBL-1 and VBL-2) were studied. A table was compiled for mutual transformations of these elements, which actually form a group.

Taking into account the demagnetizing field for samples, the annihilation field of two BP (H_x^i) is about 8 Oe; the annihilation field of two VBL (H_z^i) for a sample with $d = 50$ μm is about 10 Oe, the field is reduced with increase of d ($H_{x,z}^i$ is the true field in the sample). For the BP and VBL merging field, only one estimate from below is obtained: $H_x^i \sim 20$ Oe.

The difference in the processes of converging BP-BP and VBL-BP pairs is explained by the fact that a HNL interval between two substructure elements in the first case is compressed under the pressure of the neighboring subdomains of HNL on both sides, while in the second case, only on one side, since the VBL does not move in the field H_x and stabilizes the position of its near-surface region.

For $H_x^i > 20$ Oe an abrupt magnetization of separate areas of the crystal surface along the x axis takes place. The near-surface layers, magnetized along the x axis, are arranged periodically on opposite sides of 180-degree DW, which makes it possible to relate this with the periodic near-surface substructure of 180-degree DW observed by the authors.[4] HNL intervals with the Néel magnetization component, parallel to H_x, serve as magnetic reversal centers.

Merging of three structural elements (VBL, BP, and VBL) and also absorption of VBL by the line of intersection of 180-degree and two 90-degree DW have been observed. Using the table of mutual transformations, the result of merging of an arbitrary number of elements can be predicted.

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