MACROSCOPIC DOMAINS IN HIGH-COERCIVITY ALLOYS WITH SINGLE-DOMAIN MAGNETIC STRUCTURE

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A domain structure of a special type has been studied in specimens of magnetically uniaxial, high-coercivity alloys: single crystals of the alloy Alnico, subjected to thermomagnetic treatment, and specimens of the alloy Vicalloy, under the influence of tensile stresses at the time of observation. In both cases the domain structure has the form of bands, oriented at a certain angle to the axis of easy magnetization. This angle decreases with increase of the total magnetic anisotropy. A qualitative model for the origin of the observed domains is proposed.

1. It has been shown in a number of works[1] that macroscopic domains can be observed in the alloy Alnico in a high coercivity state; their dimensions are many times larger than the dimensions of the structural components of this alloy, which are single-domain. These single-domain formations, in consequence of shape anisotropy, are magnetically uniaxial; they are separated from one another by weakly magnetic layers. If the alloy has been subjected to thermomagnetic treatment (only on such specimens is a domain structure observed), there occurs an alignment of the long axes of the single-domain particles along the field that acted during the heat treatment. The hypothesis was advanced that the observed coarse domains are regions in which, as a result of magnetic interaction, the magnetic moments of the single-domain formations are oriented uniformly. These domains have been called interaction domains. Without pausing to review the existing experimental material,[1] we mention only that hitherto the observations have been carried out on separate crystals of polycrystalline specimens; the orientation of the crystallites was not determined. It was conjectured that the boundaries of the domains are parallel to the axis of easy magnetization. No essential differences in the form of the domain structure for low-coercivity and high-coercivity states of an alloy have been recorded.

Study of interaction domains should have value not only for understanding of the character and role of the interaction of single-domain particles in high-coercivity alloys, but also for the more general problem of investigating the special type of domain structure whose existence is due to parallel orientation of the moments of isolated ferromagnetic regions, when each region is a single domain and reverses its magnetization by the process of rotation.

It seems important to arrange experiments in which it would be possible to take rigorous account of the magnetic anisotropy, and also to regulate it deliberately. To this end, we have studied the domain structure in single crystals of the alloy Alnico, treated in a magnetic field along a definite crystallographic direction, and in polycrystalline specimens of the alloy Vicalloy, under the influence of tensile stresses at the time of observation. The alloy Vicalloy is known to consist, in the high-coercivity state, of two phases; one of the phases is ferromagnetic, the other paramagnetic. The particles of the ferromagnetic phase have dimensions of the order of hundreds of Angstroms;[2] the magnetization reversal processes occur by rotation of the vector magnetization.[3] In the presence of a large tensile stress, the magnetic anisotropy of the particles of the ferromagnetic phase increases; they become magnetically uniaxial, and the specimen as a whole acquires a magnetic texture with the texture axis along the direction of the tension.[3] Thus in the stretched state, a specimen of the alloy Vicalloy has traits in common with a single crystal of Alnico treated in a magnetic field: single-domain, magnetically uniaxial particles with a preferred orientation of the axis of easy magnetization, located in a nonmagnetic or weakly magnetic environment.

An investigation on stretched specimens of

Vicalloy has the advantage that by change of the tensile stress it is possible to control the amount of the uniaxial anisotropy over a wide range without changing the structural state of the alloy or the value of the saturation magnetization of the ferromagnetic phase. This should provide additional possibilities in the study of domain structure.

2. The Alnico alloy had the composition: 24% Co, 14% Ni, 8% Al, 3% Cu, remainder Fe. The crystals studied were obtained from a polycrystalline ingot in which the crystallites had linear dimensions up to 10 mm. The specimens were cooled from 1300 to 790°C in a magnetic field, oriented in a {100} plane along a ⟨100⟩ axis, and were quenched in oil; then they were ground, polished electrolytically, and coated on the polished surface with a layer of silicon dioxide to protect against oxidation; after this, the domain structure was observed. Then the single crystal was annealed at temperature 590 to 600°C in a vacuum. After every few hours of the annealing, the coercive force H_c was measured and the domain structure was observed, without repeated treatment of the surface. Another treatment carried out was cooling of specimens at the critical rate from 1300 to 600°C and annealing at 600°C.

The Vicalloy alloy contained 52% Co, 12% V, remainder Fe. Specimens in the form of bars were cut from a plate, subjected to annealing at 600°C for 30 minutes, and then ground and polished electrolytically or mechanically. After annealing, H_c = 200 Oe. The domain structure was observed by means of a powder suspension. The magnetic field was produced with an electromagnet.

3. Figure 1a shows the domain structure of a single crystal of Alnico, cooled in a magnetic field H_T and quenched in oil; H_c = 1 Oe. The domain structure has a form that is usual for uniaxial, magnetically soft ferromagnets. On magnetization parallel to the axis of easy magnetization, wall displacement occurs.

Figure 1b shows the form of the domain structure of the same crystal, annealed, after the thermal treatment described above, at 600°C for 28 hours; it had coercive force H_c = 300 Oe. This photograph corresponds to the state of residual magnetization of the specimen after magnetization along the ⟨100⟩ axis along which the field H_T was applied. In Fig. 1b two systems of lines are visible, at an angle φ of 8 to 10° to the direction of the field H_T. A structure of this type was observed in an external field from +1000 to −1500 Oe after magnetization in a field of +10 000 Oe.

If the magnetizing field is not parallel to H_T, then one of the systems of bands may appear, as is seen in Fig. 1c. This figure shows the structure of the same crystal (H_c = 300 Oe) after shutting off of a field of 10 000 Oe oriented at 45° to H_T. After magnetization in a field perpendicular to H_T, no domain structure arises.

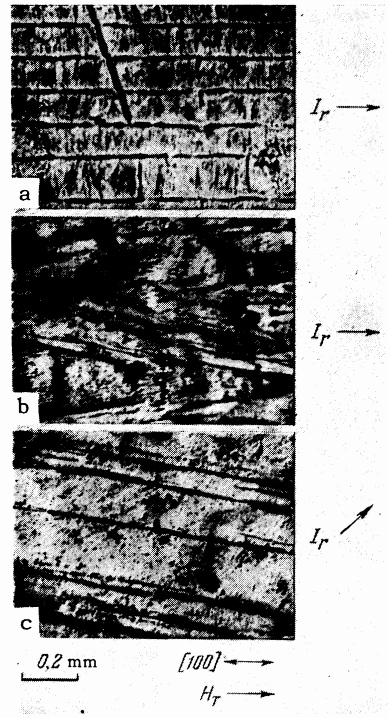

FIG. 1. Domain structure of a single crystal of Alnico in the state of residual magnetization I_r. The arrows next to "I_r" show the orientation of the demagnetizing field. a, interrupted treatment in a magnetic field H_T; H_c = 1 Oe. b, the same treatment plus annealing; H_c = 300 Oe. c, the same treatment as in case b, with magnetization at angle 45°C to H_T.

Similar pictures were obtained on single crystals with H_c between 200 and 550 Oe. Lines running at an angle to H_T are observed after even a short anneal, when $H_c \sim 30$ Oe. For $H_c \sim 100$ Oe, they are clearly apparent in the case of magnetization reversal along H_T; in the case of magnetization reversal perpendicular to H_T, there occurs a structure that is usual for the multidomain state. The angle between bands, for a given specimen, remains approximately constant as H_c varies from 30 Oe to its maximum value.

Figure 2 shows photographs of the domain structure of bars of Vicalloy in a state of elastic tension. During the observations the field was applied at an angle of 45° to the direction of the tension. The observed structures are similar to those that occur for single crystals of Alnico with magnetization at an angle to H_T. The bands in the photographs of Fig. 2 are not parallel to the direction of σ, that is the direction of the magnetic axis of the single-domain formations. The angle φ between the bands and σ decreases with increase of σ

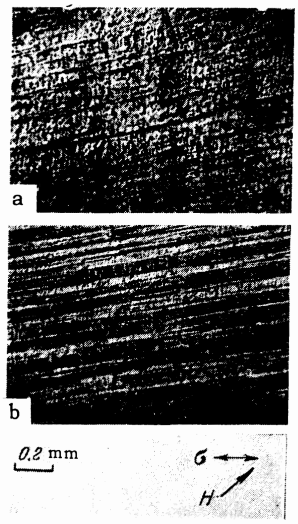

FIG. 2. Domain structure of a specimen of Vicalloy under the influence of a tensile stress σ. H is the external magnetic field during the observations. a, σ = 40 kg/mm², H = –350 Oe; b, σ = 115 kg/mm², H = –450 Oe.

(in Fig. 2a, it is 13° to 15°; in Fig. 2b, 8° to 10°). With increase of σ, the clarity of the observed picture improves; the bands become more uniform. On increase of the field that is being reversed, it can be observed that the originally narrow and dark bands broaden. Domain structure is observed in a field interval close to the coercive force. With increase of σ (and consequent increase of H_c of the specimen), the absolute value of the negative field in which domain structure is observed increases. In unstretched specimens and at small σ, no domain structure appears.

4. Thus the observed picture of macroscopic nonuniformity of the magnetization on the surface of single crystals of Alnico, in the high-coercivity state, is qualitatively different from the form of the domain structure of uniaxial ferromagnets with a multidomain magnetic structure (cobalt, manganese-bismuth, barium ferrite, or Alnico in the magnetically soft state). An important difference is the arrangement of the domain boundaries not along the magnetic axis of the specimen, but at a certain angle to it. Origination of a domain structure occurs in the process of magnetization reversal of the specimen and depends on the direction of the field being reversed. This direction determines whether two systems of bands will be observed, or one, or whether they will not originate at all (the last, for magnetization perpendicular to the magnetic axis).

The powder-deposit pictures observed on elastically stretched specimens of Vicalloy, in the high-coercivity state, have characteristics in common with the pictures observed on high-coercivity single crystals of Alnico. Specifically, on the surface of the elastically stretched specimens there appear bands oriented at a certain angle φ to the magnetic axis created by the tension. On increase of the size of the uniaxial anisotropy, which occurs in consequence of an increase of the tensile stress, there occurs a diminution of the angle φ.

The results presented are not yet sufficient for a full description of the mechanism of formation of coarse domains, which embrace a large number of single-domain particles. A qualitative picture of the formation of macroscopic domains may be offered as follows.

In the largest field, which brings the specimen to saturation along the axis of easy magnetization, the magnetization vectors of the single-domain formations are arranged parallel to this field. On decrease of the magnetizing field, or on change of its sign, there begins a turning of the magnetization vectors of the single-domain formations. This turning proceeds nonuniformly (Fig. 3): the vector magnetizations of particles indicated in Fig. 3 by the solid arrows make, during the turning, different angles with the axis of easy magnetization. The indicated turning can proceed gradually and reversibly up to a certain angle φ; after this, the particles in which this angle is reached (and the macroscopic regions that consist of such particles) change their magnetization direction discontinuously—reverse their magnetization.

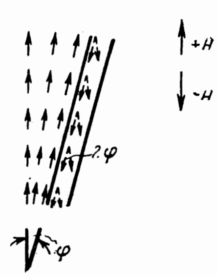

FIG. 3. Schematic representation of the process of magnetization reversal of a complex of single-domain particles.

In the magnetization-reversal process, the vector magnetizations of the particles try to keep the mutually parallel orientation that was present at saturation, since violation of this parallelism must lead to large internal stray fields. However, the influence of the demagnetizing field of the magnetically uniaxial specimen as a whole contributes a fluctuation in the macroscopic region with antiparallel orientation of the magnetization. Therefore at the time of the irreversible rotation, there originate macroscopic regions in the form of bands within which the magnetizations of the single-domain particles are parallel (or almost parallel) to one another, but the total magnetization has a component in the direction of the reversing field (Fig. 3). Possible orientations of the magnetizations of the particles inside the reversed bands are noted in Fig. 3 by dashed arrows.

As has been indicated, the rotation of the magnetizations of the particles proceeds reversibly up to a certain angle φ. The location of the particles in which this angle is simultaneously reached has the result that the boundaries of the reversed regions also make an angle φ with the direction of easy magnetization. An important consideration is that with increase of the anisotropy, the angle φ, up to which reversible rotation is possible in the particles, decreases, and the orientation of the bands approaches the direction of the axis of easy magnetization.

The same scheme can be used for a qualitative explanation of the results of the observations in which the magnetizing field is oriented at some angle to the axis of easy magnetization.

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