Origin of Brown's coercive paradox in perfect ferromagnetic crystals

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It is brought to evidence that Brown's coercive paradox results from the assumption that the shape of the crystal considered is ellipsoidal. The extremely large demagnetizing fields developed near sharp corners of a uniformly magnetized crystal cause the appearance of closure domains which serve as preexisting nuclei of the magnetization reversal process. Thus, the resulting coercive field of the crystal can be lowered by orders of magnitude from the postulated micromagnetic value. A direct experimental verification of this phenomenon is observed on highly perfect single-crystal iron whiskers.

It has been shown by Brown[1] that for a perfect ellipsoidal ferromagnetic crystal, the long axis of which coincides with an easy axis of magnetization, no deviation from saturation occurs until a reverse field H_r has reached a value of

$$H_r > \frac{2K}{\mu_0 M_s} - NM_s \ , \tag{1}$$

where K is the magnetocrystalline anisotropy constant, M_s the saturation magnetization, and N the geometric depolarization coefficient in the direction of H_r. The large discrepancies between the measured coercive field of various ferromagnetic materials and the micromagnetic value predicted by Eq. (1) have been predominantly attributed to the existence of crystalline imperfections, such as nonmagnetic impurities[2] or dislocations.[3] The disagreement between theory and experiment is usually referred to as "Brown's coercive paradox."

The fundamental experimental work of De Blois and Bean[4] on single-crystal iron whiskers has emphasized that the origin of Brown's paradox[1] might be the nonellipsoidal shape of the crystals. A tentative indication of this aspect has already been given by Shtrikman and Treves.[5] However, no direct experimental verification has been obtained so far.

The single-crystal iron whiskers used for the present investigations exhibit the simple Landau domain structure shown in Fig. 1. X-ray investigations ensure the high crystalline perfection of the samples. Additionally, scanning electron micrographs show that the crystals are bounded by perfect sharp corners. The inductively recorded quasistatic hysteresis loops yield a coercive field of 0.02 kA/m and relative remanence of 3%.[6,7] Curve (a) in Fig. 2 shows a typical magnetization curve in the as-grown state of a whisker. The linear-response region is predominantly caused by a field-induced parabolic curvature of the long 180° Bloch wall (see Fig. 1). The resulting free magnetic poles on the crystal surface and on the bowed wall create a demagnetizing field which can be characterized by a demagnetizing coefficient N of a long cylinder with the dimension ratio of the whisker,[6] i.e., the slope of the straight portion of hysteresis loop (a) in Fig. 2 is proportional to the inverse demagnetizing factor, $1/N$. Upon reaching a critical "departure field" the Landau domain structure changes irreversibly to a complicated domain structure dominated by 90° domains near the corners of the whisker[8] (see Fig. 3). This latter domain configuration exhibits a strongly reduced susceptibility caused by a gradual decrease of the closure domains. Upon reducing the external field below a critical "returning field" the Landau structure appears again leading to a

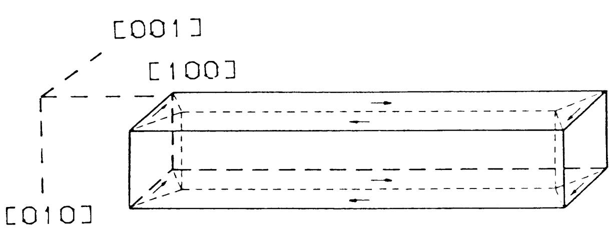

FIG. 1. Landau domain structure of an iron whisker grown in a ⟨100⟩ crystallographic direction and bounded by {100} faces.

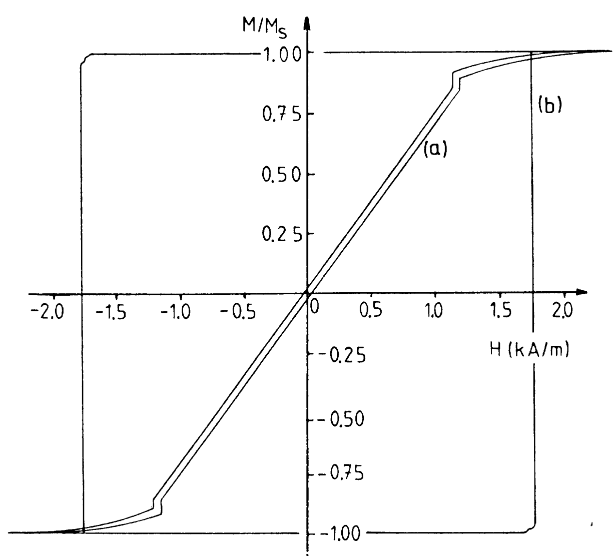

FIG. 2. (a) Magnetization curve of a whisker in the as-grown state, (b) after smoothing of the whisker tips.

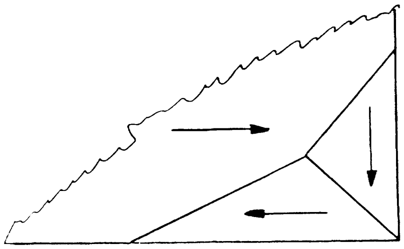

FIG. 3. Closure-domain configuration at the corner of a whisker during overall saturation.

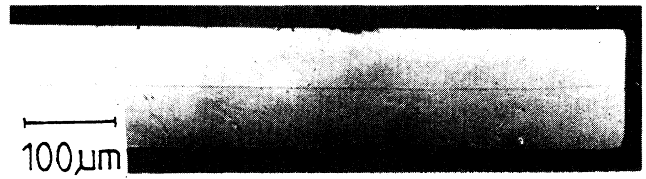

FIG. 4. Bitter pattern near a tip after smoothing of the whisker.

linear magnetization reversal [see Fig. 2, curve (a)]. It should be emphasized that the hysteresis of the magnetization loop in the as-grown state results predominantly from the difference between the departure field and the returning field of the Landau structure.

In order to investigate the influence of the sharp corners upon the magnetization process, the tips of the whisker have been carefully electropolished in CrO_3-glacial acetic acid. The Bitter pattern in Fig. 4 shows a striking modification of the demagnetized domain structure caused by the slight smoothing of the initially sharp corners. The 90° closure domains at the tips of the whisker (see Fig. 1) have been removed. As a result the magnetization curve of the whisker changes drastically [see Fig. 2, curve (b)] and becomes similar to that of a single-domain particle. During the overall saturation of the whisker no closure domains are observed in its corners. Upon reaching a critical reverse field the magnetization reversal takes place in a single jump. Thus the coercive field rises from 0.02 to about 1.8 kA/m and the relative remanence from 3% to 100%.

The above results show that the huge demagnetizing fields associated with a uniformly magnetized corner cause the formation of closure domains (see Fig. 3) which remain even during the overall magnetization of the whisker.[8,9] Upon reducing the external field the preexisting closure domains serve as the nuclei of reverse magnetization and increase their length irreversibly, until the Landau structure is formed at the returning field. Magnetization reversal will then proceed easily by reversible movement of the 180° Bloch wall. On the other hand, smoothing of the whisker tips removes the closure domains (see Fig. 4). It is assumed that the magnetization near the tips becomes inhomogeneous. Upon reaching the critical reverse field, which coincides with the coercive field of the whisker, the polarization reversal starts in the regions of nonuniform magnetization and proceeds rapidly through the whole whisker. The measured reverse field of 1.8 kA/m, which is still much smaller than the theoretical coercive-field limit of 44.8 kA/m[1] is determined by the wall-nucleation field within the inhomogeneous regions near the tips of the whisker.

In conclusion, it has been shown that sharp corners can cause considerable reductions of the coercive field and thus are a fundamental source of Brown's paradox. For the future, the computation of the magnetization curve of an ideal crystal with sharp corners seems worthwhile because of its basic as well as applied importance.

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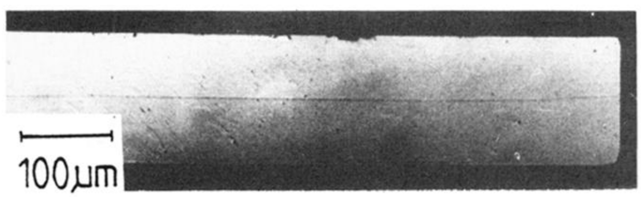

FIG. 4. Bitter pattern near a tip after smoothing of the whisker.