Possibility of small Barkhausen jumps in an ideal crystal

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The domain structure of a uniaxial ferromagnetic material in an intensified magnetic field can be altered by means of successive intermittent doublings of the period, during which the average magnetization also undergoes jumps. It is assumed that these are Barkhausen jumps.

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1. Small Barkhausen jumps in a ferromagnetic material with a domain structure are usually associated with the presence of defects. We shall examine a possible mechanism for these jumps in an ideal crystal. Let us assume that a uniaxial ferromagnetic crystal, which is unbounded in the x and y directions and has a thickness L along the anisotropy z axis, is in a magnetic field H_{0z}. The boundaries of the interdomain regions lie in the (y, z) planes. We restrict ourselves to the Kittel[1] structure, which occurs if the anisotropy constant $\beta \gtrsim 10$.[2] The crystal energy per unit area perpendicular to the z axis[3] is

$$E = M_0^2 L \left\{ 2\beta \frac{\Delta}{d} + 2\pi A_0^2 - A_0 \frac{H_0}{M_0} + \frac{d}{L} \sum_{n=1}^{\infty} \frac{A_n^2}{n} \left[1 - \exp\left(- \frac{\pi n L}{d} \right) \right] \right\}. \quad (1)$$

Here $A_0 = (d_+ - d_-)/2d$, $A_n = -(4/\pi n) \sin(\pi n d_-/2d)$, M_0 is the saturation magnetization, d_+ and d_- are the widths of domains magnetized in the direction of the field and opposite to it (positive and negative), and Δ is the thickness of the interdomain regions (nearly independent of the field). Equation (1) holds if the periodic domain structure with the period $2d = d_+ + d_-$ $(d_+ \gtrsim d_- \gg \Delta)$ is preserved as the field intensifies; according to Ref. 3, it increases with increasing field, so that each interdomain region must be displaced by a distance that increases with the distance from some initial domain. We show that another process can change the domain structure as a result of intensification of the field: successive first-order phase transitions contained in the intermittent doubled periods of the structure. Jumps occur at certain critical fields H_0, at which the maximum energy is the same before and after the jump. (We are dealing with those fields for which homogeneous magnetization is not advantageous.) We assume that these are Barkhausen jumps.[4,5] The simplest assumption is that every other domain is reversed (since the reversal of adjacent domains is less advantageous), the period of the structure is doubled, and the magnetization of the crystal changes suddenly.

For sufficiently strong fields, but lower than $H_{max} = 4\pi M_0$, the inequality $d_- \ll d \ll L$ exists. Thus,

$$E = M_0^2 L\left[2\beta\frac{\Delta}{d} - 4\pi\gamma A_0 + 2\pi A_0^2 + 4\frac{d_-^2}{Ld}\left(\frac{3}{2} - c + \ln\frac{d}{\pi d_-}\right)\right],$$

where $\gamma = H_0/H_{max}$ and $c \cong 0.58$ is the Euler constant. We have a minimum energy for

$$\frac{d_-}{d} = 1 - \gamma + \frac{2}{\pi}\frac{d}{L}(1-\gamma)[1 - c + \ln\pi(1-\gamma)]. \qquad (2)$$

A calculation shows that $E(d_0) = E(2d_0)$ for the critical value $\gamma_1 = 0.58$, $E(2d_0) = E(4d_0)$ for $\gamma_2 = 0.67$, and $E(4d_0) = E(8d_0)$ for $\gamma_3 = 0.84$ ($8d_0 \ll L$). If the field is sufficiently strong, then $d_- \ll L \ll d$ and $d/L = n_{d_0}/L$, where $n \gg 1$. Thus,

$$E = M_0^2 L\left[2\beta\frac{\Delta}{d} - 4\pi\gamma A_0 + 2\pi A_0^2 + 4\frac{d_-^2}{Ld}\left(\frac{3}{2} - c + \ln\frac{L}{d_-}\right)\right].$$

Optimization with respect to the quantity d_-/d leads to the relation,

$$\frac{d_-}{d} = 1 - \gamma + \frac{2}{\pi}\frac{d_-}{L}\left(c - 1 + \ln\frac{d_-}{L}\right). \qquad (3)$$

For a $BaFe_{12}O_{19}$ crystal[3] $\beta\Delta \approx 1.13 \times 10^{-3}$ cm and for $L = 1$ cm $d_0 \approx 3.63 \times 10^{-3}$ cm; suppose that $d/L = 10$, i.e., $n \approx 2.8 \times 10^3$. A jump in $d/L(10 \to 20)$ occurs for $E(10L) = E(20L)$; this occurs at $\gamma(10, 20) = 0.996$ and then at $\gamma(20, 40) = 0.997$ and $\gamma(40, 80) = 0.9975$. For the approximation $\gamma \to 1$ the critical H_0 values converge quickly, but for the applicability limits of the theory ($d_- \gg \Delta$) the domain structure remains energetically more advantageous than a homogeneously magnetized crystal.

2. According to Ref. 3, the potential of the intrinsic magnetic field is

$$\Phi(x, z) = 4\pi M_0 A_0 z + 4M_0 d \sum_{n=1}^{\infty} \frac{A_n}{n}\cos\frac{\pi n z}{d}\sinh\frac{\pi n z}{d}\, e^{-\frac{\pi n L}{2d}}.$$

Therefore, $H = H_1 + H_2$, where $H_1 = H_{1z} = -4\pi M_0 A_0$ and H_2 is the periodic field with the components H_{2x} and H_{2z}. Substituting d_-/d from Eq. (2), we obtain $H_{1z} = H_0 + O(d/L)$. If $d/L \ll 1$, then the field H_2 differs noticeably from zero only for $(L - 2|z|)/L \ll 1$, i.e., near the crystal surface. Consequently, it can be assumed that the intrinsic field compensates for the external field H_0 everywhere except in the regions near the surface, and a domain structure exists. In the opposite case $d_- \ll L \ll d$ no compensation occurs; however, in the presence of severe anisotropy $\beta \gtrsim 10$ the magnetization inside the domain, as before, has only the $\pm M_z$ components and, therefore, the domain structure is preserved. The M_y component also exists within the interdomain region; this is due to the fact that the inhomogeneous exchange energy $\frac{1}{2}\alpha(\partial\mathbf{M}/\partial x)^2$ in this region is also of the order of $\beta\mathbf{M}^2$ (Ref. 6).

3. The average crystal magnetization is $\overline{M} = M_0 A_0$. In relatively weak fields H_0, when the period of the domain structure is $2d_0$ (i.e., before the first jump), the magnetization increases linearly $\overline{M} = \gamma M_0 + O(d_0/L)$. For the first critical value $H_0 = \gamma_1 H_{max}$ a doubling of the period occurs, and the crystal magnetization increases

suddenly by the amount $\delta\overline{M}/M_0 = 0.13_{d_0}/L$. At $H_0/H_{max} = \gamma_2$ the jump is $\delta\overline{M}/M_0 = 0.24_{d_0}/L$, and for $H_0/H_{max} = \gamma_3$ the jump is $\delta\overline{M}/M_0 = 0.37_{d_0}/L$; thus, the jumps increase with increasing field H_0 after it reaches the critical value $\gamma_1 H_{max}$. According to Eq. (2) for $d_- \ll d \ll L$,

$$\overline{M} = M_0 \left\{ \gamma + \frac{2}{\pi} \frac{d}{L} (\gamma - 1) [1 - c + \ln \pi (1 - \gamma)] \right\}$$

between the jumps. When the field H_0 increases to a value very close to the value H_{max}, i.e., ($\gamma \to 1$), the ratio d_-/d is determined by Eq. (3); in this case the distances between the critical fields at which the jumps occur decrease together with the jumps. In the last case the increase in $\overline{M}$ between the jumps, caused by the decrease in d_-/d, is almost compensated for by the reverse change during the jumps.

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