THE MAXIMAL MAGNETIC SUSCEPTIBILITY OF POLYCRYSTALLINE NICKEL

F. D. Miroshnichenko

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The two maxima in the susceptibility are shown to arise from irreversible displacement of the 180° and 90° boundaries; the activation energy arising from the internal stresses is found to be proportional to these.

There is no theory of magnetization for the critical-field range, for no proper allowance can be made for factors of thermal, mechanical, and other origins. We have to do without a theory that explains the general trends and particular features of the curves for the magnetization and susceptibility.

Here I consider the behavior of the maximal susceptibility of a polycrystalline material from this point of view. The basis is the statistical theory of spontaneous magnetization, although Vonsovskii [1] has pointed out that this is applicable only under the following very special conditions: 1) all types of boundary between domains are equivalent; 2) there is a single-valued relation of the phase concentrations n_i to the magnetization I; and 3) the material is completely isotropic. I assume that these conditions are largely complied with in an annealed material that has not been deformed in any way. There are domains with 180 and 90° boundaries; I assume that the 180° ones are mutually equivalent, as are the 90° ones. The entire specimen may be considered as a mixture of two media if we assume that the two sets of boundaries are displaced independently: 1) one with 180° neighbors; 2) one with 90° neighbors.

The internal stresses should be of random orientation if there is no texture caused by deformation, so each of these media will be quasi-isotropic and should have an n_i uniquely related to I. It is then considered [2-5] that the statistical theory of susceptibility is applicable.

Brown gives the differential equations

$$\frac{\partial^2\Phi}{\partial u_i \partial u_\kappa} = A \frac{\partial\Phi}{\partial u_i} \frac{\partial\Phi}{\partial u_\kappa}, \tag{1}$$

$$n_i = \frac{\partial\Phi}{\partial u_i}, \tag{2}$$

in which Φ is a function of the u_i.

The solution to (1) is $e^{-A\Phi} = \Sigma f_i(u_i)$, the $f_i(u_i)$ being defined by

$$\sum n_i = \sum \frac{\partial\Phi}{\partial n_i} = 1.$$

Then

$$\frac{\partial f_i(u_i)}{f_i(u_i)} = -A du_i,$$

$$\ln f_i(u_i) = -Au_i + AC_i = -A(u_i - C_i),$$

in which the C_i are arbitrary constants. Then $f_i = e^{-A(u_i - C_i)}$ and

$$\Phi = -\frac{1}{A} \ln \sum e^{-A(u_i - C_i)}. \tag{3}$$

From (2)

$$n_i = \frac{e^{-A(u_i - C_i)}}{\Sigma e^{-A(u_i - C_i)}}. \tag{4}$$

From (4) we have

$$I = I_s \frac{\Sigma h_\kappa e^{-A\,(u_\kappa - C_\kappa)}}{\Sigma e^{-A\,(u_\kappa - C_\kappa)}}\,. \tag{5}$$

The energy of magnetization is $u_k = -I_s H h_k$.

We now put the C_k as $C_k = Ch_k$; then

$$I = I_s \frac{\Sigma h_\kappa e^{A\,(I_s H - C) h_\kappa}}{\Sigma e^{\ A\,(I_s H - C) h_\kappa}}\,. \tag{6}$$

The essential point here is that the C_k are constants for reversible displacements but are variables for irreversible ones.

We consider the maximal susceptibility due to displacement of domain boundaries, so the C are variable. We average (6) over all grain orientations to get

$$I = I_s \frac{\int\limits_0^\pi e^{A\,(I_s H - C)\cos\vartheta} \cos\vartheta \sin\vartheta\, d\vartheta}{\int\limits_0^\pi e^{A\,(I_s H - C)\cos\vartheta} \sin\vartheta\, d\vartheta} = I_s L\,(W), \tag{7}$$

in which $W = A\,(I_s H - C)$ and $L\,(W) = \mathrm{cth}\, W - \frac{1}{W}$. Finally, we put $C = -H_\infty I_s$; then $W = AI_s(H + H_\infty)$, so the susceptibility is

$$\varkappa = \frac{\partial I}{\partial H} = \frac{\partial I}{\partial W}\cdot\frac{\partial W}{\partial H} = AI_s^2 L'\,(W) = AI_s^2\left(\frac{1}{W^2} - \frac{1}{\mathrm{sh}^2 W}\right). \tag{8}$$

Here $f\,(W) = \frac{1}{W^2} - \frac{1}{\mathrm{sh}^2\, W}$ and is shown in Fig. 1; the function is somewhat reminiscent of a gaussian curve, being nearly symmetrical about the f(W) axis in plot of f(W) against W. Then $f\,(W) = \frac{1}{W^2} - \frac{1}{\mathrm{sh}^2\, W}$ may be treated as showing that magnetization (and reversal) occur most readily when $H = -H_\infty$; if we represent the specimen as in [6, 7], the magnetization may be said to change abruptly when the external field becomes such as to correspond to the energy $HI_s = -H_\infty I_s$. The various H_∞ fall around H_s (which may be taken as the most probably value for H_∞), as in uniaxial crystals magnetized along the easy axis or as in stretched materials with positive magnetostriction [8-12]; hence a large Barkhausen jump is to be expected.

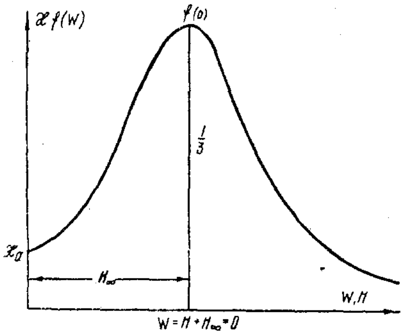

Fig. 1. The graph function $f\ (W) = \frac{1}{W^2} - \frac{1}{\mathrm{sh}^2\ W}$.

Then $C = -H_\infty I_s$ varies from one region of spontaneous magnetization to another when the displacement is irreversible; it may be considered as the activation energy arising from the internal stresses. Figure 1 shows that $f\,(W) = \frac{1}{W^2} - \frac{1}{\mathrm{sh}^2\, W}$ has its peak at W = 0, so $\varkappa = AI_s^2 L'(0)$ has a maximum value of

$$\varkappa = \frac{1}{3} AI_s^2. \tag{9}$$

This is the maximal susceptibility $\varkappa_{max}$; the case envisaged here is spontaneous magnetization with 180° neighbors, and hence we put (9) as

$$\varkappa_{max\uparrow\downarrow} = \frac{1}{3} AI_s^2. \tag{10}$$

The constant A here has the dimensions of reciprocal energy and may be put as $A = b/\lambda_s\sigma_i$, in which b is a constant of the order of one and $\lambda_s\sigma_i$ represents the constant for the energy of the internal stresses. The maximal susceptibility associated with displacement of 180° boundaries is then

$$\varkappa_{\max\uparrow\downarrow} = \frac{bI_s^2}{3\lambda_s\sigma_i} = \frac{K}{\sigma_i}, \qquad (11)$$

in which $K = bI_s^2/3\lambda_s$; formula (11) implies that this follows a hyperbolic law.

The 90° boundaries give analogous formulas, except that the constants $C = -H_\infty I_s$ appearing $L(W) = \operatorname{cth} W - \frac{1}{W}$, and $L'(W) = \frac{1}{W^2} - \frac{1}{\operatorname{sh}^2 W}$ will differ from those for 180° boundaries. A suitable notation here is

$$C_{\uparrow\downarrow} = -H_{\infty\uparrow\downarrow} I_s - \quad \text{for} \quad \text{co } 180°\text{- boundaries}$$
$$C_{\uparrow\rightarrow} = -H_{\infty\uparrow\rightarrow} I_s - \quad \text{for} \quad \text{c } 90°\text{- boundaries}$$

This implies a second maximum in the susceptibility at $\varkappa_{\max\uparrow\rightarrow} = \frac{K}{\sigma_i}$, arising from irreversible displacement of the 90° boundaries.

The two contributions to the susceptibility are additive when the boundaries in the two media are displaced independently;

$$\varkappa_{\max} = \varkappa_{\max\uparrow\downarrow} + \varkappa_{\max\uparrow\rightarrow} = \frac{2K}{\sigma_i}. \qquad (12)$$

The $\varkappa = f(H)$ curve should thus have two peaks under certain conditions, as actually occurs for nickel wire annealed in hydrogen at 900°C for 2 hr. I used the ballistic method, with care near the region of $\varkappa_{\max}$; care was also taken to measure the H corresponding to this as closely as possible, namely H_∞. Figure 2 gives the results, which show that there are two peaks separated by 0.2 Gauss. This small separation shows why they have previously been overlooked for polycrystalline materials, where low resolution in H has been usual.

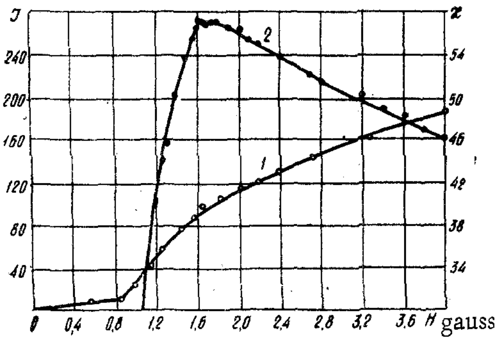

Fig. 2. 1) Magnetization curve and 2) susceptibility for soft polycrystalline nickel wire.

In addition, (12) implies that the two peaks should move together as σ_i alters; this I examined by subjecting the wire to plastic extension. Figure 3 gives the results for eight specimens of extremely soft nickel wire.

Figure 3 shows that $\varkappa_{\max} H_\infty$ = constant as a function of H over a wide range; this, with the $\varkappa_{\max}$ of (12), gives

$$H_\infty = K_1 \sigma_i, \qquad (13)$$

in which $K_1 = \text{const}/2K$.

This shows that H_∞ is proportional to the internal stress; i.e., the activation energy for boundary displacement is proportional to the stress.

Conclusions

1. There are two peaks $\varkappa_{\max\uparrow\downarrow}$ and $\varkappa_{\max\uparrow\rightarrow}$ in the susceptibility, which are due to displacement of 180° and 90° boundaries.

2. Theory and experiment show that the activation energy $W = -H_\infty I_s$ is proportional to the internal stress.

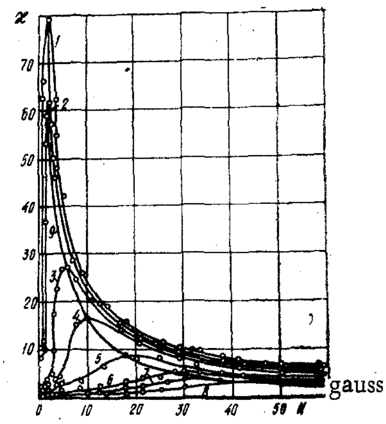

Fig. 3. Relation of ϰ to magnetizing field for plastically stretched soft nickel wire with ε of 1) 0%; 2) 0.165%; 3) 0.66%; 4) 1.74%; 5) 3%; 6) 7.7%; 7) 11%; 8) 14.7%.

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Zaporozhe Pedagogic Institute