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Origin of the Linear Term in the Expression for the Approach to Saturation in Ferromagnetic Materials*

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There has been confusion for many years over the origin of the a/H term in the expression for the approach to saturation, $M/M_s = 1 - a/H - b/H^2 + cH$, observed in many ferromagnetic materials. A calculation is presented which suggests that residual internal strain contributes significantly to this term. Internal strain has previously been thought to contribute only to the b/H^2 term. It is further suggested that the a/H term has been overemphasized and has validity only over a limited region of the H axis. The effect of internal strain is deduced from consideration of a problem concerning nonhydrostatic strains induced in slightly porous magnetic material subject to external hydrostatic pressure. A comparison with recent experimental work supports the calculation.

I. INTRODUCTION

There has been continued interest for many years in explaining the various terms which occur in the expression for the approach to saturation observed experimentally in many ferromagnetic materials:

$$\frac{M}{M_s} = 1 - \frac{a}{H} - \frac{b}{H^2} + cH \; . \qquad (1)$$

The cH term has been adequately explained in terms of paraprocesses. The constant in the b/H^2 term has been shown to be

$$b = \frac{8}{105} \frac{K^2}{M_s^2} + \frac{3}{5} \frac{\lambda_s^2 \langle \sigma_i^2 \rangle_{\text{av}}}{M_s^2} \; , \qquad (2)$$

where the first part is due to crystalline anisotropy,[1] and the second part, derived by Becker and Polley,[2] is considered to be the influence of internal strain on the approach to saturation.

The origin of the a/H term is not well understood. Calculations by Brown[3] have shown that dislocation effects can contribute to this term, while Néel[4] has concluded that stray fields due to nonuniform magnetization may bring about forces which would contribute to this term. The origin of this term has been investigated experimentally by Parfenov and Voroshilov.[5] One significant observation noted by these authors was that the constants a and b varied similarly with increasing internal strain in the magnetic material. However, they were unable to substantiate either theory and concluded by still questioning the nature of the a/H term.

The present calculation was motivated by a recent experimental investigation concerning the magnetic properties of slightly porous polycrystalline ferromagnetic materials when subject to external hydrostatic pressure.[6] The porous material, initially strain-free, experiences nonhydrostatic strain in the vicinity of pores when an external hydrostatic pressure is applied. These nonhydrostatic strain regions, coupled with the magneto-elastic properties of the material, will significantly affect the magnetization curve. In that work (Ref. 6) the magnetization exhibited a strong linear dependence on the variable P/H in the approach to saturation region of the curve. This vividly illustrates the a/H dependence in Eq. (1) and suggests an origin of the constant a.

Specific objectives of the present calculations are the following:

(a) to propose a model for the magneto-elastic behavior of the porous material which predicts the P/H dependence of the magnetization and determines the region of the magnetization curve for which the dependence is valid. Results are compared with the experimental work of Ref. 6;

(b) to suggest that the calculation in (a) is relevant in cases where there is no external applied pressure, but where there are residual internal strains due to internal defects. This would imply that internal strain contributes to the a/h dependence. It was previously thought to contribute only to the b/H^2 dependence. The primary conclusion is that the a/H term is a myth, or has at least been overemphasized. It has approximate validity in a limited range (H neither too large nor too small) of the magnetization curve;

(c) to interpret previous observations (primarily those of Parfenov and Voroshilov) which have not been understood in terms of the conclusion of (b). These interpretations lend further support to the conclusion.

This article is presented in the following order: In Sec. II a model for the magnetic behavior of the porous material subject to external hydrostatic pressure is formulated and a sufficient magnetic energy expression derived. In Sec. III a series solution for the magnetization curve is obtained but is found poorly convergent in the region of interest. A complete numerical solution is presented in Sec. IV. In Sec. V the results of Secs. III and IV are compared with the experimental work of Ref. 6. In Sec. VI extension of this calculation to the magnetic behavior of material with residual internal strain is suggested and discussed.

II. MODEL FOR POROUS MATERIAL

The first problem, as stated in the Introduction, is to predict the magnetization curve in the approach to saturation region for porous polycrystalline ferromagnetic material subject to external hydrostatic pressure. Porosities contemplated are less than 5%. This is consistent with the work of Ref. 6. Generality is not important here since the ultimate goal is to infer the origin of the a/H term in actual ferromagnetic material from the results of the porosity problem.

The model used to describe the porous material will be developed from the following assumption: The average behavior of an aggregate of random-sized and -shaped cavities can be represented by the behavior of a spherical cavity in an infinite isotropic elastic medium. This assumption has been used fruitfully in obtaining the dependence of elastic moduli on porosity in polycrystalline material.[7,8] An excellent photomicrograph of the situation contemplated is shown on p. 218 of Smit and Wijn.[9] Illustrated is 5% porous manganese-zinc ferrite.

To obtain the magnetization curve in the region of interest, a magnetic energy expression which adequately describes the material is required. The total energy is usually written[10]

$$E = E_H + E_{\mathrm{me}} + E_K + E_{\mathrm{ex}} + E_{\mathrm{d}} \ . \tag{3}$$

The first term, $E_H = -\vec{M}_s \cdot \vec{H}$, is the interaction energy with the external applied field. The remaining four terms are, respectively, the magneto-elastic, crystalline anisotropy, exchange, and demagnetizing energies. The magneto-elastic energy will be obtained first. The last three terms are ignored in the present work. Justification is offered later in this section.

To obtain an expression for the magneto-elastic energy, knowledge of the strain distribution about a spherical cavity is required.[11] Referring to Fig. 1, the strain field at a distance r from a cavity of radius a, subject to a limiting boundary condition of hydrostatic pressure P and zero traction on the cavity surface, is

$$e_{ij} = -\tfrac{1}{3} K_T P \delta_{ij} + \frac{P}{4\mu} \frac{a^3}{r^3} \; 3\frac{x_i x_j}{r^2} - \delta_{ij} \ . \tag{4}$$

K_T is the compressibility and μ is the shear modulus. It should be mentioned that this approach ignores the magnetostrictive property of the material. The strain error incurred by this approximation is small. Magnetostriction strains are on the order of 10^{-5}. Strains considered in this work