Shock-Induced Anisotropy in Ferromagnetic Material. I. Domain-Theory Analysis of Single-Crystal Behavior*

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Shock-induced demagnetization produced by strain-induced anisotropy is considered in cubic single-crystal ferromagnetic material. Equilibrium thermodynamics, along with established methods of ferromagnetic domain theory, are used to predict energy expresssions, magnetization curves, and domain structure in the magnetic material behind the shock wave. In particular, specific expressions for the exchange energy and magnetic self-energy are obtained. They are predicted to increase as the fourth root of the strain and are small compared to the induced anisotropy energy in the region of large elastic and plastic strain. Calculations are made for yttrium iron garnet.

I. INTRODUCTION

When magnetic material is subject to a strong shock wave and at the same time biased by an external magnetic field applied parallel to the shock front, a reduction in magnetization is observed. By this method shock waves are used to study the magnetic behavior of materials subject to extreme states of stress. In ferromagnetic material three mechanisms have been identified as contributing to shock-induced demagnetization. These are first-order crystallographic phase transitions in which total demagnetization is observed to occur,[1,2] second-order phase transitions between ordered and disordered magnetic states,[3,4] and shock-induced anisotropy in which nonhydrostatic strains along with magnetoelastic properties of the material produce deviations from magnetic saturation.[2,5-7] This paper is concerned with the last.

The problem of shock-induced anisotropy is best understood by considering the model used to describe it. Referring to Fig. 1, consider an infinite half-space of ferromagnetic material contained in the region $x > 0$. Planar impact at the interface $x = 0$ creates a plane shock wave S propagating in the positive x direction. This creates in the region behind the shock wave an infinite slab of ferromagnetic material subject to a state of uniform uniaxial strain.[8] During and following shock initiation, the ferromagnetic material is subject to a transverse magnetic field H_e sufficient to induce magnetic saturation in the material in front of the propagating shock wave. Behind the shock wave a reduction in magnetization occurs. This is the observed shock-induced demagnetization and is, in the present work, a consequence of the magnetoelastic properties of the material.

Theoretical consideration of shock demagnetization produced by shock-induced anisotropy parallels methods used in predicting other ferromagnetic behavior. This consists of writing an energy expression sufficient to describe the magnetic and mechanical properties of the ferromagnetic slab behind the shock wave and minimizing this energy with respect to some parameter which determines the magnitude of transverse magnetization in the slab. By this method the equilibrium magnetization and, hence, shock demagnetization, is determined. These general statements will be more fully described in Secs. II–VI. Early work on the shock-induced anisotropy effect considered a total energy consisting of the interaction energy $E_H = -\mathbf{H}_e \cdot \mathbf{M}_s$ along with the magnetoelastic energy E_{me} and the crystal anisotropy energy E_k.[2,5,7] This is sufficient to predict shock-induced demagnetization. These early papers represent a significant contribution to the understanding of shock-induced anisotropy. They, however, ignored energy terms which are known to significantly contribute to ferromagnetic behavior, viz., the exchange energy and the demagnetizing energy. These energy terms were considered in a micromagnetic theoretical treatment of shock-induced anisotropy.[9] However, micromagnetic theory is, at present, mathematically cumbersome and limited in application. The gap between earlier work and the sophisticated methods of micromagnetic theory is spanned by the ferromagnetic domain theory. Its concepts are well developed in the literature.[10] The primary objective of the present work is to apply the established methods of ferromagnetic domain theory to the problem of shock demagnetization produced by shock-induced anisotropy. Specific objectives are as follows: The magnetic domain structure expected to nucleate after shock passage will be predicted. A total magnetic energy expression will be obtained. In particular, explicit expressions for the exchange and demagnetization energy will be determined. The error resulting from ignoring these terms, as has been done in previous work, will also be determined. Magnetization curves for the material behind the shock wave will be obtained and conditions necessary for shock demagnetization to occur ascertained.

The present work will be restricted to the shock-induced anisotropy effect in cubic single-crystal ferromagnetic material. This is preparatory to understanding the similar effect in polycrystalline material, which is the topic of the following paper.[11] The region of strain considered in this work will be in the elastic range but at strains which are a sizable fraction of the Hugoniot elastic limit of the material. This is consistent with the order of strain obtained in earlier magnetic shock work.[2,5,6] Extension to the plastic region requires an additional assumption.[12]

This article is directed to workers in the field of shock-wave physics or people interested in the magnetic re-

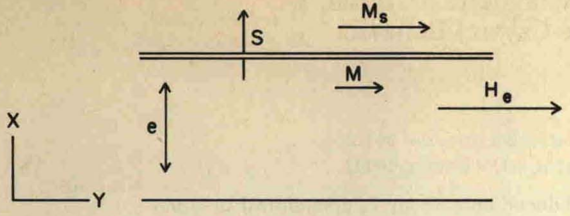

FIG. 1. Geometry for shock-induced demagnetization. Infinite half-space of ferromagnetic material in region $x > 0$. Uniaxial strain in region behind the shock S. Applied field H_e in transverse direction. Reduction in magnetization occurs across the shock front.

sponse of material to dynamic loading. To the specialist in magnetics, for whom the methods of ferromagnetic domain theory are well known, some of the concepts will be self-evident.

Presentation of this article is in the following order: The various energy terms required in the analysis are defined in Sec. II. This section also includes a discussion of the induced anisotropy effect. A common misconception has held that within the validity of conventional first-order magnetoelastic theory, ignoring crystal anisotropy energy, the axis of uniaxial strain defines an easy or hard direction of magnetization. This is not true for arbitrary crystal axis orientation with respect to the axis of uniaxial strain. An interesting consequence of this is that total shock-induced demagnetization is not expected, regardless of the magnitude of strain. In Sec. III, a ferromagnetic domain-theory analysis is presented for the shock-induced anisotropy effect. In Sec. IV, magnetization curves and conditions for shock demagnetization are determined. The results are applied to yttrium iron garnet in Sec. V and discussed in terms of relative contributions of the various magnetic energy expressions to the shock-induced anisotropy effect. Experimental shock demagnetization results on polycrystalline YIG are presented in the following article.[11]

II. THERMODYNAMIC ENERGY

Thermodynamics of a rigid ferromagnet are used to describe the shocked material.[13] A rigid ferromagnet is a thermodynamic system for which the functional dependence of the energy $E(S, M_i, e_{ij})$ is reduced to the dependence $E(S, M_i)$ by maintaining the state of strain e_{ij} constant. M_i is the magnetization and S is the entropy. A rigid ferromagnet implies that each lattice point is stationary and is not subject to motion by the forces present. The strain e_{ij} is maintained constant by the inertia of the material after passage of the shock wave and will remain so until relieved by perturbing waves (a problem only when finite boundaries are considered).[14]

A total thermodynamic energy expression sufficient for a phenomenological description of a rigid anisotropic ferromagnet is given by

$$E = E_H + E_d + E_{\mathrm{ex}} + E_K + E_{\mathrm{me}}. \tag{1}$$

Each term will be identified briefly. Complete developments can be found in many excellent treatments in the literature.[10,13,15,16] The elastic energy is neglected in this expression. A function of strain, only it will be constant in a rigid ferromagnet.

The first terms is

$$E_H = -\mathbf{H}_e \cdot \mathbf{M}_s. \tag{2}$$

This is the interaction energy of the magnetic material in the external applied field $\mathbf{H}_e$.

The second term is

$$E_d = -\tfrac{1}{2}\mathbf{H}_d \cdot \mathbf{M}_s. \tag{3}$$

This is the self-energy or demagnetizing energy of the magnetic system. $\mathbf{H}_d$ is the demagnetizing field and originates from magnetic surface and volume poles. This energy is intrinsically positive. Domain structure in ferromagnetic material occurs in an attempt to reduce the demagnetizing energy.

The third term is the ferromagnetic exchange energy. The magnetization gradients are found to be adequate thermodynamic variables for a phenomenological description of this energy. A quadratic form

$$E_{\mathrm{ex}} = A_{ij} \frac{\partial \alpha_K}{\partial x_i} \frac{\partial \alpha_K}{\partial x_j}$$

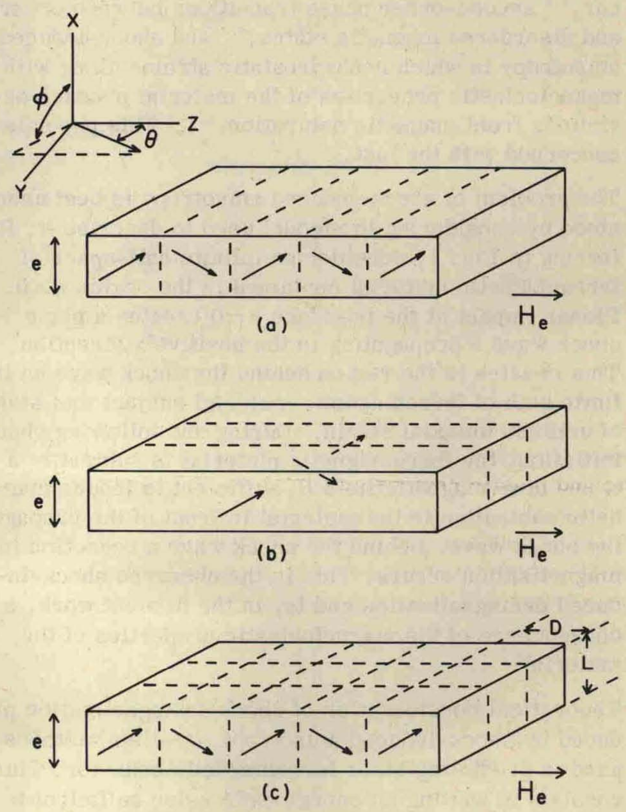

FIG. 2. (a) Model for platelike domain structure perpendicular to the applied field. (b) Model for platelike domain structure parallel to the applied field. (c) Model for needle-shaped domain structure oriented along axis of uniaxial strain. Polar angles define direction of magnetization during transition through domain wall.