Shock-Induced Anisotropy in Ferromagnetic Material. II. Polycrystalline Behavior and Experimental Results for YIG[†]

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The theory of shock-induced demagnetization produced by strain-induced magnetic anisotropy is considered in cubic polycrystalline ferromagnetic material. Analysis of the averaging procedure required to predict the polycrystalline behavior reveals the importance of magnetic grain interaction. Magnetization curves for extreme assumptions of interacting grains and independent grains are determined. Experimental shock demagnetization data are obtained for polycrystalline yttrium iron garnet in the region of large elastic strain (approximately $\frac{1}{3}$ and $\frac{2}{3}$ of the Hugoniot elastic limit). Results support the independent grain assumption.

I. INTRODUCTION

Previous experimental work on magnetic shock-induced anisotropy has been, without exception, on polycrystalline ferromagnetic or ferrimagnetic material.[1-5] In polycrystalline material, the single-crystal shock-induced anisotropy discussed in the preceding paper[6] occurs in individual crystallites. Primary concerns of the present work are the prediction of average polycrystalline magnetic behavior and the magnetic interaction between grains which must be known or assumed before the average behavior can be predicted unambiguously. Previous theoretical work on shock-induced anisotropy in polycrystalline materials has assumed, for the sake of expedience, uniform magnetization within the material.[3,7] This assumes a substantial magnetic interaction between grains and is not necessarily the correct assumption. In the present work extreme assumptions concerning the magnetic grain interaction are formulated. They are referred to as the interacting grain and independent grain assumptions, respectively. Polycrystalline magnetic behavior is determined for each assumption.

Actual magnetic behavior will be bounded by the two extreme predictions. Experimental objectives of the present work are to determine which magnetic behavior predicted from the extreme assumptions concerning magnetic grain interaction more closely represents actual behavior. Experimental shock demagnetization curves for polycrystalline yttrium iron garnet were obtained with the gas gun facilities at Washington State University. Data obtained in the region of large elastic strain (approximately $\frac{1}{3}$ and $\frac{2}{3}$ of the Hugoniot elastic limit) support the independent grain assumption. From these results, conclusions concerning relative contributions of the various energy terms affecting the magnetic behavior are obtained.

In Sec. II, the general polycrystalline averaging procedure is briefly summarized. Shock demagnetization curves are then obtained for the interacting grain and independent grain assumptions. The physics implied by each assumption is discussed. The experimental method and material characterization are reported in Sec. III. In Sec. IV, the experimental results are presented. In Sec. V, results are discussed in terms of the magnetic energies contributing to the shock-induced anisotropy effect.

II. THEORY

The prediction of a polycrystalline material property from its equivalent single-crystal property is a problem confronted in many areas of physics. The approach, quite similar in every case, requires an averaging of the single-crystal property for an arbitrarily oriented crystallite over all crystal orientations.[8] A complicating factor is that an arbitrary crystallite interacts not only with the external forces but also with other grains in the polycrystalline material. This grain interaction can be mechanical (through stresses), electrical, or magnetic. In most cases, the interaction is not understood.

Examples of such material properties are elastic constants, dielectric constants, magnetostriction constants, and conductivities. In each case, basic assumptions concerning the grain interaction must be formulated before progress can be made. For instance, in the case of elastic constants two extreme assumptions have been used. One assumption is that uniform strain exists throughout the polycrystal.[9] The other is that uniform stress prevails.[10] Experiment favors neither, usually being closer to an arithmetic average of the results of the two assumptions.[11] Similar assumptions are made in obtaining polycrystalline magnetostriction constants.[12–15]

In the present problem, the state of strain behind a plane shock wave in a theoretically dense cubic polycrystal is assumed uniform.[16] The speculation of present interest concerns the magnetic grain interaction. This is an interaction of current interest about which little is known.[17–18] In analogy with the method used to obtain polycrystalline elastic constants, this development will define extreme assumptions concerning the magnetic grain interaction and then consider each individually.

One extreme is that material crystallites interact with sufficient strength to cause a cooperative collinear alignment of the magnetization vectors throughout the specimen. The other extreme is that magnetic grain interaction is negligible and that each grain individually seeks equilibrium determined only by the requirements of the induced anisotropy field and external magnetic field. These assumptions will be called the interacting grain assumption and the independent grain assumption, respectively.

A. Interacting Grain Assumption

The interacting grain assumption used by Shaner and Royce[3,4] during early work on shock-induced anisotropy leads to a mathematically tractable averaging process. Domain structure in a polycrystalline ferromagnet is usually on an intragrain scale. This is due to high crystal anisotropy energy and large-angle grain boundaries which make continuous domains across grain boundaries energetically unfavorable. There are cases, however, such as in material subject to cold working, in which a degree of crystal orientation allows an extragrain domain structure.[19] In the present effect, the easy direction of magnetization is determined not only by the crystallographic axis, but also by the axis of uniaxial strain.[20] Thus, the effect of the shock wave is to create a condition of magnetic texture defined by the direction of uniaxial strain behind the shock wave. It might be reasonable to expect an extragrain domain structure to nucleate after passage of the shock wave.

Continuing this argument, consider a spherical grain within a domain of uniform magnetization. Magnetization in this grain could deviate from the direction of uniform magnetization only by creating surface poles on the grain boundary. The energy associated with this is

$$E=\frac{4}{3}\pi M_s^2\cos\gamma ,$$

where M_s is the saturation magnetization and γ is the angle defining the deviation of the grain's magnetization from the direction of uniform magnetization. In YIG, at typical shock stresses, this energy is of the same order as the strain-induced anisotropy energy. Hence, there would be strong torques attempting to maintain uniform magnetization throughout a domain.

The interacting grain assumption is $\mathrm{M}\cdot\mathrm{H}$ *is uniform throughout the field.* This simply states that the projection $M_s\cos\theta$ along the direction of the applied field is constant for arbitrary crystal orientation. Prediction of the magnetization curve requires construction of an appropriate energy expression. This will consist of the interaction energy

$$E_H=-\mathrm{M}\cdot\mathrm{H}_e \qquad (1)$$