Memorandum M-3035

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Electrical Engineering Department

MASTER'S THESIS PROPOSAL

TITLE: An Investigation of Some Parameters which Influence the Magnetic Characteristics of Ferrites

BRIEF STATEMENT OF PROBLEM:

Recent theories have been advanced concerning the squareness of the hysteresis loop and the dynamics of the magnetic switching mechanism in polycrystalline ferrites. These theories require evaluation. The important parameters of these theories, grain-to-grain alignment of the direction of magnetization, domain-wall energy density, and the saturation moment, will be investigated in this thesis.

HISTORY OF PROBLEM:

Magnetic materials with a square hysteresis (B-H) loop are used in information storage devices.[1,5] This application has stimulated the development of both metallic and nonmetallic ferrite materials possessing a square B-H loop. This magnetic property has been obtained for polycrystalline metals by producing a grain-to-grain alignment of the magnetization direction throughout the material. The grain-to-grain alignment is usually established by one of the following techniques:

a. Orientation of the crystallites,

b. Establishment of shape anisotropy in grains or precipitates,

c. Magnetic anneal when effective, or

d. Application of a high tensile or compressive stress.

In the case of ferrites, orientation of the crystallites has been feasible only for permanent-magnet materials.[2] In the ferrites establishment of shape anisotropy is not feasible and a magnetic anneal is not effective. Application of a compressive stress does produce a square B-H loop in some ferrites.[3,4] In other ferrites, however, very square B-H loops have been obtained without recourse to any alignment technique whatsoever.[5]

A theory of B-H loop squareness has been recently proposed.[6] The basic concept considered in this theory is the nucleation of domains of reverse magnetization at grain boundaries. Free poles are present on the grain-boundary surface due to a grain-to-grain misalignment of the magnetization directions. Nucleation of domains of reverse magnetization becomes energetically favorable when the energy required to create a domain of reverse magnetization is equal to or less than the gain in energy due to the redistribution of free poles on the surface.

Only the energy involved in the creation of a domain of reverse magnetization would be a function of the externally applied field if it is assumed there is negligible rotation of the directions of magnetization due to the externally applied field. A positive direction of the applied field will be defined as that favoring a complete flux reversal from the given state. In the case of a saturated magnetic material, there would not be domains of reverse magnetization nucleated until the applied field is increased to the point where the energy required to create a domain of reverse magnetization is sufficiently low. Once nucleation occurs, irreversible domain-wall motion would proceed to reverse the magnetization of the material if the applied field is sufficiently high to maintain wall motion.

The necessary condition for a material to have a square B-H loop is that the applied field at which nucleation occurs be greater than the field necessary to maintain domain-wall motion. When this condition is expressed in terms of fundamental parameters the following relationship is obtained:

$$L \omega^{*2} < 60 \sigma_w,$$

where L is a mean grain diameter, ω^* is the grain-surface pole density, and σ_w is the energy density for a 180° domain wall. The surface pole density ω^* is proportional to the saturation moment and varies inversely with the grain-to-grain alignment. In metals the saturation moment is so high that the condition for a square B-H loop can be obtained only with high grain-to-grain alignment of the magnetization directions. In ferrites the condition for squareness may be satisfied without high grain-to-grain alignment since the saturation moment of the ferrites is an order of magnitude less than that for the metals. However, the value of the domain-wall energy density σ_w is unknown. Therefore, a considerable grain-to-grain alignment may also be a necessary condition for squareness in ferrites.

There have been various experiments performed which are relevant to the problem of the square B-H loop in ferrites. The chemical composition of these materials has been found to be the main variable in obtaining the squareness of the B-H loop.[7] Most square B-H loop ferrites in production today are mixed magnesium-manganese ferrites. Microstructure studies of the magnesium-manganese ferrites have shown that the compositional region of ferrites possessing a square B-H loop is one of solid solution and is bounded by regions with either precipitates or low Curie temperatures. The lamellar precipitates obtained in some ferrite compositions have an essentially random orientation in the material. This is indicative of a corresponding random orientation of the grains.

The squareness of the B-H loop of these materials is not determined by the geometry of the sample as fired. This has been shown by cutting small toroids from large specimens of square B-H loop ferrites at various orientations and comparing their magnetic properties. No significant difference could be found regardless of the orientation in the original sample.

Very low macroscopic magnetostriction effects have been observed on toroids of square B-H loop ferrites,[8] whereas high macroscopic magnetostriction effects have been observed on toroids of non-square B-H loop ferrites.[9] It has been noted that materials, both metals and ferrites, which had low squareness but high macroscopic magnetostriction could be made to possess high squareness by the application of an orienting stress.[3,4,10]

The square B-H loop materials used in computer storage devices must have a response to low-pulse excitation that has a duration in the order of microseconds.[5] Therefore, it is desirous to minimize both the time for flux reversal in these materials and the necessary pulse excitation to produce this flux reversal. A theory of the flux-reversal mechanism in polycrystalline materials has been advanced[11] using the model of expanding cylindrical domains of reverse magnetization. The shape of the voltage response of a polycrystalline ferrite to pulse excitation can be explained mainly on the basis of the change in effective domain-wall area. A figure of merit for the magnetization reversal is defined as the switching coefficient $S_W = (H_m - H_o)\tau$, where τ is the time required to reverse the magnetization, H_m is the applied magnetic field, and H_o is the threshold-field value at which the average domain-wall velocity is zero.

The equation of motion of a cylindrical, 180° domain wall has been derived.[12] The switching coefficient has been derived from this equation in terms of fundamental parameters as

$$S_W = \frac{\beta d}{2 I_s \langle \cos \theta \rangle},$$

where β is the viscous damping coefficient in the equation for domain wall motion, d is a measure of the average distance a domain wall travels in the time τ, I_s is the saturation moment, and θ is the angle between the direction of magnetization and the applied field.

The viscous-damping coefficient β is proportional to the domain-wall energy density σ_W. Therefore, there are three important parameters which enter both the condition for a square B-H loop and the expression for the switching coefficient S_W. These parameters are (1) the general alignment of the magnetization directions, both from grain to grain and with respect to the direction of the applied field, (2) the domain-wall energy density σ_W, and (3) the saturation moment I_s. Since it is desirable to obtain a maximum B-H loop squareness and minimum S_W, it is instructive to make a chart indicating the relative effect of an increase of the important parameters on both B-H loop squareness and the switching coefficient S_W.

Increase of the Parameter	Effect on the B-H loop squareness	Effect on the Switching Coefficient Sw
Alignment	Increase	Decrease
σ_w	Increase	Increase
I_s	Decrease	Decrease

The importance of alignment is very definitely shown, since it is the only parameter which can produce both desirable effects at the same time.

The switching coefficient Sw has been measured on both metals and ferrites.[11] The viscous-damping coefficient β has been measured on single crystals of magnetite and nickel ferrite.[13] I_s has been measured on a stoichiometric series of mixed magnesium-manganese ferrites.[14] It should be noted, however, that these data have been obtained by various workers on different compositions. Therefore because of chemical instability in ferrites these data should not be used in the evaluation of theory.

DEFINITION OF PROBLEM

The problem of this thesis is the investigation of the important parameters in the theories of B-H loop squareness and the switching mechanism in the ferrites. There is the possibility that a macroscopic alignment of the magnetization directions does exist. A strong argument for the existence of an alignment is that the B-H loop of some non-square ferrites can be made square by the application of an orientating external stress. Since the squareness of these ferrites is so clearly a function of the alignment, the possibility of squareness existing in other ferrites without such an alignment should be questioned. The cause of macroscopic magnetostriction is due to either rotation effects or 90° domain-wall motion. Therefore, the low macroscopic magnetostriction effects in square B-H loop ferrites also point to a gross alignment of the domains.

If a grain-to-grain alignment exists in these materials, a mechanism must also exist and be compatible with the following two disturbing facts: (1) there does not exist a preferred orientation of grains, and (2) the properties of a square B-H loop are independent of the direction of the applied field. Both of these experimental facts indicate that the crystalline anisotropy of these materials would tend to act against any alignment effects. Consideration of this problem has led to the following possible solution. Since rather high intrinsic magnetostriction exists for many non-square ferrites, it is not unreasonable to expect the same for ferrites with square B-H loops. The magnetoelastic energy caused by internal magnetostriction effects would be a minimum for complete grain-to-grain alignment of the magnetization directions. Therefore various degrees of alignment could be possible depending on the relative magnitude of the energy of crystalline anisotropy and the magnetoelastic energy due to magnetostriction. A preliminary calculation indicates that considerable alignment will result when these energies are of the same order of magnitude. The direction of this alignment could be established simply by the application of a moderate field if the average effect of the crystalline anisotropy is sufficiently low.

Since the importance and possibility of a grain-to-grain alignment is evident, the actual alignment of the domain magnetization directions in ferrites will be measured. The technique that will be used is similar to that used by others on materials possessing a preferred orientation.[15] This technique utilizes macroscopic magnetostriction relationships which are functions of the angular configuration of the directions of domain magnetization within the material. The parameter that is determined by this technique is the average value of $\cos^2\theta$, where θ is the angular deviation of the direction of magnetization from a given preferred direction and the average is taken over the whole sample. For the case of a completely random or isotropic angular distribution of the directions $\overline{\cos^2\theta} = \frac{1}{3}$, whereas for the case of complete alignment $\overline{\cos^2\theta} = 1$. Therefore the value of $\overline{\cos^2\theta}$ is an index of alignment.

An expression has been developed for the 180° domain-wall energy density, viz. $\sigma_w = 2\sqrt{K_{eff}A}$,[16] where K_{eff} is the effective anisotropy and A is the magnetic exchange parameter. The effective anisotropy is the sum of crystalline anisotropy and magnetoelastic energies; i.e. $K_{eff} = K + \frac{9E}{2}\lambda^2$, where K is the crystalline anisotropy constant, E is Young's modulus, and λ is the isotropic magnetostriction constant. A measure of λ will be obtainable from the alignment measurements. However, a satisfactory measurement of the K in a polycrystalline material is very difficult, especially if the magnitude of K is low. Therefore, single-crystal measurements are planned for the measurement of both K and λ. The magnetic exchange parameter A is proportional to the Curie point.[17] Therefore, measurement of the Curie point will permit an estimate of the value of A.

The saturation moment I_s will be obtained on both polycrystalline and single-crystal samples. To provide further information all experimental data in the thesis will be obtained as functions of temperature.

The viscous damping coefficient β can only be measured when the domain configuration is known and simple. Therefore, measurements of this parameter are restricted to single crystals.[13] Work of this nature will be done in conjunction with this thesis by others. This work would provide additional data for the thesis.

The data on B-H loop squareness and the switching coefficient S_w will be measured on all polycrystalline samples. A correlation of all data then will permit evaluation of the theories of B-H loop squareness and the switching mechanism.

PROCEDURE

1. Design and Construction of Equipment

The equipment necessary for measuring the magnetostriction of disc samples will be designed and built. The magnetostrictive strain will be measured by the compensated-wire-gage method.[13]

2. Polycrystalline Measurements

The samples will be fired as discs and will consist of square B-H loop ferrites. Alignment, isotropic-magnetostriction coefficient, and saturation moment will be measured on disc samples as functions of temperature. Then the center will be cut out of the discs, changing the samples into toroids. The B-H loop squareness and the switching coefficient will be measured on the toroids as functions of temperature. Finally, measurement of the Curie point will make the data complete.

3. Single-Crystal Measurements

Thin discs oriented in a $\{110\}$ plane, cut from available single crystals of ferrite, will be used for measurement of the magnetostriction coefficient, anisotropy constant and saturation moment as functions of temperature. Then, time permitting, a "window frame" having each side in a $\langle 111 \rangle$ direction will be cut from each disc. The domain configuration in the "window frame" would be simple and known. Therefore, the viscous-damping coefficient can be determined[13] as a function of temperature. Very few single crystals are available. This fact and the hazards of sample preparation may seriously hamper this phase of the thesis.

4. Theoretical Development

A theoretical development of the grain-to-grain-alignment mechanism will be made if an actual alignment is found to exist. This theory would then be evaluated in the light of the experimental data of the thesis.

5. Evaluation of Theories and Formulation of Results

The theories of B-H loop squareness and the switching mechanism in ferrites will be evaluated on the basis of the experimental data.

EQUIPMENT NEEDS

The Lincoln Laboratory facilities will be available for the necessary construction work. Sample preparation facilities and all necessary equipment is also available in the Lincoln Laboratory through the joint cooperation of Groups 35, 37 and 63.

ESTIMATED DIVISION OF TIME

1.	Preparation of Proposal	50 hours
2.	Development of Theory and Literature Search	100 hours
3.	Construction of Equipment	100 hours
4.	Experimental Work	200 hours
5.	Correlation of Results	50 hours
6.	Preparation of Thesis Report	100 hours
7.	Total	600 hours

SIGNED: Philip K. Baltzer
Philip K. Baltzer

DATE: Sept. 20, 1954

PKB:md

SUPERVISION AGREEMENT

The problem described herein seems adequate for a Master's Thesis. The undersigned agrees to supervise the research and evaluate the thesis.

SIGNED: John B. Goodenough
Dr. John B. Goodenough
DDL Staff Member

BIBLIOGRAPHY

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