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Comparison of Magnetoelastic Energy Losses and Magnetic Hysteresis in Ferromagnetic Materials

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In the present work it is shown that in several samples of ferromagnetic materials, with medium coercive forces, magnetic hysteresis energy losses in a saturation loop are higher than, but of the same order as, magnetoelastic energy losses in a stress cycle described between values of stress not far from the yield point.

Moreover, it is observed that the law that expresses the magnetoelastic energy loss of a stress loop as a function of the difference between maximum remanence $J_r(\tau)$ (measured at the maximum value of stress) and the initial value $J_r(0)$ (measured on material at rest) is of the type,

$$E=K[\Delta J_r(\tau)]^n,$$

where E is the energy loss and n is an exponent comprised between 1.2 and 2.2.

This law is very similar to the Steinmetz law, with the value of ΔJ_r substituted for the value of J (intrinsic induction at the tip of a magnetic loop).

I

Ferromagnetic materials, as is well known, show a high value of internal friction which, as was observed by Becker and Kornetzky[1] and Zacharias,[2] markedly decreases when the material is brought to magnetic saturation or is heated above the Curie temperature. (For a complete bibliography on the problem see the books of Becker and Döring[3] and Bozorth.[4]) Two of the authors[5] have shown in a previous article that the high value of internal friction is due to Weiss domain motion induced by mechanical stress; this movement is foreseen by domain theory and confirmed by several experimental results.[6] To draw these conclusions, the ratio J_r/J_s (where J_r= retentivity and J_s= saturation intrinsic induction) was assumed to be an index of domain motion,[7,8] and for several materials curves of the ratio J_r/J_s and curves of the magnetoelastic internal friction, both as functions of the applied stress, were compared. Magnetoelastic internal friction was defined as the magnetic part of the energy loss per unit volume and per mechanical cycle. In order to separate this part of the loss from the purely mechanical or viscous loss, which is always present, the magnetoelastic loss was measured as the difference between a measure of the total internal friction and a measure of the same on a saturated specimen. In that work it was observed that both curves show the same shape and show abrupt changes of slope at practically identical values of the stress. It was then concluded that the high value of internal friction of ferromagnetic materials was induced by domain motion under the applied stress.

The purpose of this paper is to compare the values of the losses in mechanical and magnetic hysteresis loops when the alteration (disregarding the sign) of domain structure, produced by magnetic field or by mechanical stress, is the same.

We have not been able to date to find the relation which establishes the equivalence between magnetic field and stress as an extension of the theory of Brown,[9] keeping in mind the well-known fact that in one case we are concerned with domains at 90° and in the other with domains at 180°. We therefore limited ourselves to finding the empirical relation between the values of the magnetoelastic energy loss and the variation $\Delta J_r(\tau)=J_r(\tau)-J_r(0)$ of the remanence, where $J_r(\tau)$ is

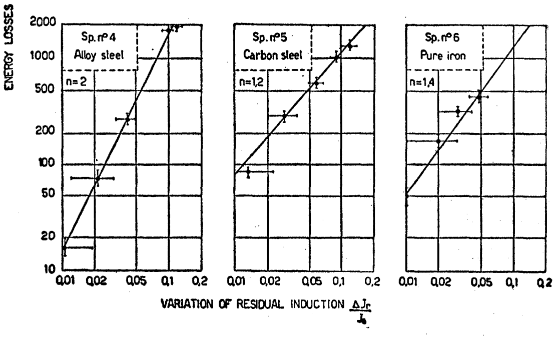

FIG. 1. Magnetoelastic energy loss values for different materials as functions of $\Delta J_r/J_s$. The reported energy loss is an average value in the specimen cross section.

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[1] R. Becker and M. Kornetzky, Z. Physik 88, 634 (1934).

[2] J. Zacharias, Phys. Rev. 44, 116 (1933).

[3] R. Becker and W. Döring, *Ferromagnetismus* (J. Springer, Berlin, 1939), pp. 357–382.

[4] R. M. Bozorth, *Ferromagnetism* (D. Van Nostrand Company, Inc., New York, 1951), pp. 699–712.

[5] A. Ferro and G. Montalenti, J. Appl. Phys. 22, 565 (1951).

[6] R. M. Bozorth, J. phys. et radium 12, 308 (1951).

[7] R. M. Bozorth, Z. Physik 124, 519 (1948).

[8] G. Montalenti, Nuovo cimento 7 (1950).

[9] William Fuller Brown, Jr., Phys. Rev. 75, 147 (1949).

TABLE I. The magnetoelastic losses observed on the maximum stress cycle which the material can stand without yielding, and the corresponding energy loss area of a magnetic loop up to saturation.

No.	Material	Coercive force Asp/m	Saturation intrinsic induction Wb/m^2	J_r/J_s initial value ($\tau=0$)	J_r/J_s maximum stress in the loop	Maximum magneto-elastic energy losses, joule/m³	Saturation magnetic hysteresis, joule/m³	Ratio between max. magneto-elastic losses and magnetic hysteresis to saturation
1	Cast nickel	600	0.61	0.52	0.60	480	1720	0.28
2 and 3	Alloy steel quenched and tempered	1200	1.91	0.74	0.66	3100	7800	0.40
4	Idem	1300	1.91	0.77	0.65	3300	8500	0.38
5	Carbon steel $C=0.4$ percent quenched and tempered	1000	1.97	0.67	0.56	2250	4500	0.49
6	Pure annealed iron	320	2.13	0.51	0.46	525	2630	0.20
7	Armco iron[a]	80	2.15	...	...	340	720	0.45

[a] Source, for magnetoelastic losses, Boulanger (reference 10); for magnetic hysteresis R. A. Chegwidden, Metal Progress **54**, 705 (1948).

measured when the mechanical stress reaches the maximum value for the mechanical loop under consideration, and $J_r(0)$ is measured when the mechanical stress is zero. The meaning of $\Delta J_r(\tau)$ will be more clearly explained later.

II

The measurement methods have been amply described in a preceding paper.[5] Internal friction measurements have been carried out using a torsion pendulum with a frequency of about 4 *Hz*. It is to be observed that magnetoelastic losses in a stress cycle are largely independent of frequency, as was already shown by other authors[4,10] and was confirmed by the authors in preliminary tests. In our case the frequency was varied between about 1 and 80 *Hz*. The test piece was rigidly clamped at one end to a heavy bench and at the other to a flywheel free to turn on the axis of the test piece. Energy loss values were deduced from the natural decrease in oscillations of the flywheel after an initial impulse. Measurements of the J_r/J_s ratio under stress were carried out in a Neumann permeameter, with a special attachment applying static torque to the ends of the specimen. The stress being torsional, the observed values both of losses and of J_r/J_s are to be considered as mean values in a specimen with shearing stresses increasing linearly from center to surface. The data of the present paper refer only to the tests carried out on samples in which there was significant variation of the J_r/J_s ratio; i.e., in which, under stress, domains had moved sensibly from the rest position. It was observed, in accordance with Boulanger,[10] that, for all samples examined, for low values of stress the magnetoelastic losses increase with the cube of the stress itself, thus giving evidence of a behavior analogous to that of the same material in a low magnetic field (Rayleigh). In this region it was not possible to test whether there was also any slight elastic variation of the J_r/J_s ratio, because these low changes of domain orientation are below the sensitivity of the measurement method (±2 percent). For higher values of the magnetoelastic losses, if these are plotted on logarithmic paper (Fig. 1) as functions of the variation of J_r (i.e., of the difference between the value measured at the maximum stress of the mechanical cycle and the initial value at rest), it was observed that, within experimental error, the points lie on straight lines. Then the following relation holds:

$$E=K[\Delta J_r(\tau)]^n,$$

where E is the energy loss and n is found to be an exponent lying between 1.2 and 2.2. For magnetic hysteresis losses in all the materials tested, the law of Steinmetz with exponent about 1.6 holds; this was experimentally confirmed by the authors. It may be concluded that a similar law is also valid for magnetoelastic losses when ΔJ_r is substituted for J.

At this point it should be noted that ΔJ_r and J have very similar physical meanings. In fact J, as is evident, is the sum of the projections on the field direction of the vectors which may be assumed to represent domain magnetizations, and whose orientation is a function of the applied field. As this sum is zero when the material is unmagnetized, J is the variation with field of the projection, starting from the initial distribution. Similarly, it is easy to see that ΔJ_r is the variation of the projection on the field direction of the domain magnetizations induced in this case by the stress. Thus, the observed validity of a law relating magnetoelastic energy losses and ΔJ_r, very similar quantitatively to the law of Steinmetz, lends evidence to the thought that the process from which magnetoelastic losses arise in a stress cycle is of the same type as magnetic hysteresis; i.e., there is a Barkausen effect due to the stress applied.

In Table I are shown and compared the magnetoelastic losses observed on the maximum stress cycle which the material can stand without yielding, and the corresponding energy loss area of a magnetic loop up to saturation. The magnetoelastic loss values in the table correspond to the case of uniform stress in the specimen, equal to that at the surface, and have been deduced analytically from the observed values by taking into account the fact that the stress increases

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[10] C. Boulanger, Rev. mét. **255** (1949).

linearly from the central axis, where its value is zero, to the external surface where its value reaches a maximum. It may thus be seen that the two values of maximum energy losses, magnetoelastic and magnetic, are of the same order of magnitude.

From these results it is not clear whether the differences observed between the two values are to be attributed to the fact that, on materials with not too low coercive forces, stresses below the yield point are unable to orient the domains completely in one direction, or to the fact that in one case 90° domains and in the other 180° domains participate in the process. For these reasons the question of the interpretation of the observed results still remains open.

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An Hysteresis Effect in the Transmission of Electrons through Thin Dielectric Foils*

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The relative transmission of monoenergetic electrons through a dielectric foil suspended in vacuum has been observed to depend upon the previous history of the foil. A plot of this transmission against energy of incident electrons shows something resembling a type of hysteresis loop. Experiments are discussed which give evidence that this hysteresis loop is produced through the collection of negative charge within the foil.

I. INTRODUCTION

THE many nuclear and electronic phenomena which depend upon the passage of electrons through matter have made experimental studies of such a process of considerable interest. In this laboratory one of the chief reasons for desiring information on this subject is for the purpose of determining the relative transmission of beta-particles through Geiger-Müller (G-M) counter windows. Since the ratio of the number of beta-particles actually entering the sensitive region of the G-M counter to the number striking the outer surface of its window depends both upon the absorption and upon the scattering of the particles within the window, the ratio is not easily obtained from theoretical considerations.

A method utilizing the electrostatic acceleration of beta-particles from the source of a thin lens spectrometer[1] is being use to study this effect as it actually appears in the window of a G-M counter. It was thought advisable to have, if possible, in addition, some independent check on the results. The apparatus constructed for this purpose has led to some interesting results with regard to the transmission of electrons through nonconducting matter, but has not necessarily served as an independent check of the results of the other study.

II. APPARATUS

For these studies electrons were accelerated from a type of electron gun, focused by a semicircular, uniform field magnetic spectrometer, and collected in a Faraday cage. The magnitude of the charge thus collected was measured by means of a Lindemann electrometer. A movable window assembly was placed immediately in front of the Faraday cage. By proper rotation of the window assembly a zapon foil could be alternately inserted into or removed from the path of the beam of electrons. This arrangement was constructed as an insert for the 5.7-cm radius of curvature magnetic spectrometer.[2] This insert is shown in Fig. 1.

There are certain distinct differences between the two methods of attacking the problem. In the first place, the electron currents are orders of magnitude apart. In the G-M counter experiment individual electrons are recorded (in range of 10^{-16} to 10^{-19} ampere). In the experiment described by this paper electron currents of the order of magnitude of 10^{-10} ampere were collected by the Faraday cage. Secondly, whereas gas is always in contact with one surface of the G-M counter window, the foil on the rotatable foil holder always existed within a relatively well-evacuated region.

Because of the larger electron currents involved, the conditions appear, so far as applications are concerned, to approach more closely to many electronic problems than to the nuclear problem for which we attempted to use it.

The mechanical fragility of the thin zapon foils makes it difficult to weigh the foils without damaging them. For this reason, it has become the practice in this laboratory to specify the thickness of thin G-M counter windows in terms of the lowest energy electron

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* Assisted by the joint program of the ONR and AEC.

† Now Ensign, U. S. Navy.

[1] C. H. Chang and C. S. Cook, Nucleonics 10, No. 4, 24 (1952).

[2] G. E. Owen and C. S. Cook, Rev. Sci. Instr. 20, 768 (1949).