A CONTRIBUTION TO THE THEORY OF FERROMAGNETISM

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Abstract

Relation of permeability and hysteresis to atomic magnetostriction.—In permalloy, as shown in the preceding paper, magnetostriction changes sign at about 81 percent Ni, hysteresis losses can be made vanishingly small near this composition, and these effects are not due to the special alignment of crystals. It is suggested that in every ferromagnetic material the process of magnetization involves (1) intra-atomic changes, presumably changes in the orientation of electron orbits, governed by quantum dynamics and independent of environment; and (2) inter-atomic changes (stresses and strains). The inter-dependence of the inter-atomic changes and the intra-atomic changes is conveniently described as atomic magnetostriction. On this view, hysteresis loss and magnetic hardness are due to the energy required to produce, in succession, the local deformations associated with changes in the magnetization of single atoms or small groups of atoms. High initial permeability and low hysteresis loss in permalloy are explained as resulting from locally compensatory atomic magnetostrictions of the nickel and iron atoms in small groups. The fundamental differences in the magnetic behavior of Fe, Ni and Co are attributed to differences in their atomic magnetostrictions. Other differences are attributed to differences in the mechanical properties which alter the energy expended when atomic magnetostriction takes place.

THE fact that certain nickel-iron alloys are much more easily magnetized than either nickel or iron is not explained by any existing theory of ferromagnetism. Ewing's suggestion, made many years ago, that soft annealed iron probably has less coercivity than any other magnetic substance,[1] still appeared plausible until the announcement of the discovery of permalloy.[2] The explanation of permalloy demands, therefore, some revision of our ideas regarding ferromagnetism in general.

From the very beginning, it has been evident that discontinuities of some kind had to be introduced into the explanation of ferromagnetism, so that it is here perhaps that the quantum theory should have had its most natural application. Delay in making such an application has occurred, it would seem, because hysteresis has been so conspicuous in ordinary magnetic materials that the reversible processes discussed by the quantum theory have been obviously unsuitable to explain all of the facts to be covered by an adequate theory.

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[1] J. A. Ewing, Magnetic Induction in Iron and Other Metals, 3rd edition, 1900, p. 315.

[2] H. D. Arnold and G. W. Elmen, J. Frank. Inst. **195**, 621-632 (1923).

In seeking the cause for the inadequacy of the older theories it is necessary to discover where each of them introduced unwarranted hypotheses. A recent review[3] makes comparison between the older theories particularly easy. It appears after a little study that none of them has taken sufficient notice of the fact that the medium, the behavior of which they attempt to describe, is really discontinuous. Some[4] of the theories are quite obviously faulty in this respect, introducing intrinsic fields of force to a greater or less extent, and thereby avoiding consideration of the physical basis of magnetic retentivity and hysteresis. Others[5] begin with the atoms but introduce what amounts to the assumption of a continuous medium when large groups of atoms are pictured as undergoing simultaneously equal changes in magnetization.

A theory free from the objection just raised has recently been proposed by Ewing[6] and is sufficiently physical in its basis to permit of experimental test. It demands considerable complexity within the ferromagnetic atom since it regards the principal ferromagnetic characteristics as all due to intra-atomic properties. It, too, suggests no reason for the peculiarities found in permalloy and, in fact, seems to deny the possibility of their occurrence, since in an alloy we would not expect to find the individual atoms more symmetrically surrounded by their neighbors than in a pure metal, and Ewing's new theory makes a highly symmetrical enviroment of every atom essential to magnetic softness.

Magnetostriction,[7] the change in dimensions accompanying magnetization, has proven even more difficult to explain than ferromagnetism itself. No quantitative agreement has been reached between predictions based on theories of magnetostriction and the observed effects of mechanical stress upon magnetization. It should be noted that these theories also disregard the atomic structure of matter.

Until a short time ago it was permissible to postulate within the ferromagnetic atom almost any sort of mechanism which seemed necessary to the theorist. Now, however, that information is available in regard to the magnetic behavior of silver vapor[8] and the paramagnetism of ions in solution[9] it appears that the atomic structures responsible for magnet-

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[3] E. M. Terry and J. Kunz, Bull. Nat. Res. Coun. **3,** [3], 113-213 (1922).

[4] Theories of Weiss, Frivold, Gans, loc. cit.[3]

[5] Theories of Ewing, Honda, Honda and Okubo, loc. cit.[3]; cf. K. Honda, Dictionary of Applied Physics, **3,** 515-526 (1922).

[6] J. A. Ewing, Proc. Roy. Soc. **A100,** 449-460 (1922).

[7] S. R. Williams and S. L. Quimby, Bull. Nat. Res. Counc., **3,** [3], 214-234 (1922).

[8] W. Gerlach and O. Stern, Zeits. f. Phys. **8,** 110-111 (1921); **9,** 349-352, 352-353 (1922).

[9] B. Cabrera, Journ. de Phys. (6), **3,** 443-460 (1922).

ism cannot be very different from those already proposed to explain the emission and absorption of radiation.[10] The fact that ferromagnetism occurs in a very limited group of elements in the atomic series appears[11] to support the conclusions as to atomic structure derived by applications of the quantum theory to optical and x-ray emission and absorption spectra. If the arguments in favor of these structures are sound there is no place left within the ferromagnetic atoms for special mechanisms to account for magnetic hysteresis or other causes of energy dissipation on a large scale.

It is the purpose of this paper to show how division of the problem of ferromagnetism into two parts, and the introduction of a suitable connecting link between these parts permits the construction of a simple theory adequate to explain the new experimental results and consistent with what we already know of atomic structures and atomic processes.

The most natural possible division is that between processes which occur wholly within single atoms and processes which involve more than one atom, i.e., between intra-atomic and inter-atomic processes.

The first assumption will be that intra-atomic changes are governed by quantum dynamics, and in particular that the component, parallel to the applied field, of the magnetic moment of any individual atom changes abruptly, if at all. Such changes in the magnetization of an atom will occur, one after another, as the applied field is gradually raised to values which can supply the necessary energy. It need not here be considered whether or not a very weak applied field will establish a single direction within the material, with respect to which the magnetic moment of every atom is spatially quantized. Neither is it important for the present purpose to decide whether or not the absolute value of the magnetic moment of an atom, or only the direction of its axis, undergoes abrupt changes. The essential thing implied by the first assumption is that the principal changes in magnetic moment parallel to the applied field are to be considered as abrupt and as spatially discrete.

The second assumption will be that an abrupt change in the magnetization of an atom, of the sort just postulated, is accompanied by a change in that atom which is independent of the environment in which it may be placed.[12] This change affects the forces which the atom exerts upon its

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[10] W. Gerlach, Phys. Zeits. **24**, 275-277 (1923); P. S. Epstein, Science (2), **57**, 532-533 (1923); A. Sommerfeld, Phys. Zeits. **24**, 360-364 (1923); Zeits. f. Phys. **19**, 221-229 (1923).

[11] R. Ladenburg, Zeits. f. Elektrochem. **26**, 262-274 (1920); N. Bohr, Zeits. f. Phys. **9**, 1-67 (1922); L. W. McKeehan, J. Frank. Inst. **197**, 583-601, 757-786 (1924).

[12] The logical necessity for assuming the change to be independent of the characteristics of neighboring atoms was pointed out by Professor P. Ehrenfest in a private discussion.

neighbors so that the body of which it is a part tends to change in dimensions. The nature of the changes in forces which take place may be inferred from the change in the over-all dimensions of measurable bodies consisting wholly of atoms of the kind considered. The atomic changes which must occur to explain gross magnetostriction will conveniently be designated as atomic magnetostriction.

The third and final assumption is that magnetic hardness and hysteresis in measurable amount are due primarily to inter-atomic stresses set up by atomic magnetostriction, and therefore are dependent not only upon the type of atom which is magnetized but also upon the mechanical properties of the particular piece of metal of which it forms a part. In hard magnetic materials the changes involved in atomic magnetostriction meet great resistance and require the supply to the atoms, through the application of intense magnetic fields, of large amounts of energy. In soft magnetic materials the same changes meet little resistance and can therefore occur in weaker applied fields.

Hysteresis is to be regarded as due to the shocks upon the structure resulting from the sudden changes of force between atoms involved in atomic magnetostriction. A part of the energy so emitted by the atom will be dissipated at once, appearing as heat. Another part will be stored temporarily as potential energy of local strains. If these strains are relieved by further magnetization their energy will also degenerate into heat. If not, a part of this energy will be available for demagnetizing the material when the applied field is diminished, thus being responsible for the difference between the values of saturation intensity and remanence in closed magnetic circuits.

Externally applied agents, with the single exception of magnetic fields, must be supposed to act upon the magnetization of the individual atoms through their primary effect upon those inter-atomic forces which can also be set up or altered by atomic magnetostriction. Crystalline structure, affecting as it does the distribution and magnitude of such forces in different directions, should have, in pure materials at least, a considerable effect upon magnetization in different directions.

The cause of atomic magnetostriction is to be looked for in the changes of electronic arrangement which occur when the atom changes its magnetization. Speculations have been made upon this phase of the subject[13] but the details are unessential to the argument here presented.

The magnetization of a pure metal, consistently with these assumptions, may be pictured as follows. Slight inhomogeneity of conditions

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[13] L. W. McKeehan, loc. cit.[10]

throughout the material will determine the spatial distribution of the atoms which change their magnetic states in a weak applied field. Further magnetization of the atoms originally affected, or of adjacent atoms of the same kind, will be hindered by the forces set up by atomic magnetostriction, i.e. the further increase of these forces against the elasticity of the material will require an increase in the applied field. The process at first proceeds, therefore, by the successive magnetization of widely distributed atoms. The distribution of these atoms, located at points where the unfavorable stresses are least, tends to become more uniform as the field is increased. Consideration of the unmagnetized atoms shows that at first the number of these which are similarly situated with respect to those already magnetized will increase, affording a supply of atoms capable of changing their magnetic states at about the same value of applied field in a later stage in the process. When this group is being magnetized the rate of increase in permeability reaches a maximum in what has recently been described as the leg[14] of the magnetization curve. It is in this stage of the process that the Barkhausen effect (noise of magnetization) is also a maximum.[15]

The remarkable ease with which permalloy may be magnetized is striking evidence for the correctness of the theory outlined in the preceding paragraphs. Nickel, as is well known, shortens when longitudinally magnetized, while iron, at least until it is almost completely saturated, lengthens under the same conditions. Their gross magnetostrictions being opposite in kind the second assumption demands that their atomic magnetostrictions also be opposite in kind, and that this difference persist in nickel-iron alloys. It is accordingly to be expected in these alloys that local stresses set up, for example, by the magnetization of a nickel atom will be partly relieved by magnetization of an adjacent iron atom, and vice versa. Magnetization in a properly proportioned alloy of this type should be able to spread continuously from any point where it begins and should require but little increase in the applied magnetic field to produce saturation. The proper proportion of nickel and iron should be about that at which gross magnetostriction vanishes.[16] Hysteresis should be much diminished by the simultaneous magnetization of small groups of nickel and iron atoms in such proportion that the changes in the forces exerted by the group upon its neighbors is a minimum. Such cooperative changes, requiring little energy, should be rela-

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[14] V. Karapetoff, Science (2), **59**, 440 (1924).

[15] E. P. T. Tyndall, Phys. Rev. (2), **24**, 439-451 (1924).

[16] O. E. Buckley and L. W. McKeehan, preceding paper in this issue.

tively probable, as compared with changes in the magnetization of single atoms. The remanence should be relatively great because no considerable unrelieved strains would ever exist during the process of magnetization. Since inter-atomic forces would be modified but little during the entire process, the effect of crystalline structure should be, as it is,[16] unimportant in such a material.

It will be observed that the fundamental differences in magnetic behavior between the three ferromagnetic elements are here to be attributed to differences in their atomic magnetostrictions, and that the modifications in the magnetic characteristics of a single element by alloying, heat-treating, or mechanical working are to be attributed to differences in the readiness with which local strains may be set up and relieved. That condition of each magnetic material in which it is most difficult to produce the types of local strain associated with its atomic magnetostriction should be magnetically hardest. The close connection between magnetic and mechanical hardness is a strong argument in favor of the reality of atomic magnetostriction.

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