THE SIGNIFICANCE OF MAGNETOSTRICTION IN PERMALLOY

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Abstract

Magnetostriction in permalloy, measured by McKeehan and Cioffi,[1] confirms qualitatively the existence of atomic magnetostriction, as previously proposed, and the explanation, based thereon, for high magnetic permeability and low hysteresis in these alloys. The effect of tension upon magnetostriction suggests that orientation of the magnetic axes of iron and nickel atoms precisely like that due to the application of magnetic fields may be effected by mechanical stresses within the elastic limit. Acceptance of this view makes it possible to explain the large effects of tension upon magnetic hysteresis and the observed relation between the changes in electrical resistance produced by tension and by magnetization. The occurrence of a reversal of magnetostriction in a stretched wire containing 80 percent Ni is covered by the same explanation. A connection between magnetic hysteresis and mechanical hysteresis is suggested and the molecular field postulated by Weiss is interpreted as the integrated effect of local mechanical stresses.

Introduction

THE preceding paper[1] reports measurements on the magnetostriction of permalloys covering a wide range in composition, and the effect of tension upon the magnetostriction of permalloys covering a narrower range. This paper will discuss the results of these experiments, and of others previously reported, in the light of a theory[2] which attributes changes in the external dimensions of a body during its magnetization to changes in the immediate neighborhood of individual atoms as these atoms contribute to the magnetization by aligning their magnetic axes. Such atomic magnetostriction was assumed by the author to explain the loss of energy in magnetic hysteresis. It served at the same time to connect the intra-atomic changes—in orientation and energy—which the theory assumed to be basic, with inter-atomic changes like those due to gross mechanical strains and to the more local strains associated with cold-working, alloying, and other processes which alter the mechanical and magnetic properties of metals. This theory will be referred to herein as the theory of atomic magnetostriction, or more briefly, as the theory.

The theory of atomic magnetostriction is found adequate to explain the newly discovered facts of experiment, and gains in definiteness by including them in its field of application.

[1] McKeehan, L. W., Cioffi, P. P., Phys. Rev. (2), **28** 146–157 (1926).

[2] McKeehan, L. W., Phys. Rev. (2), **26,** 274–279 (1925).

Discussion

The first point to be emphasized is that in pure nickel (and *a fortiori* in the other materials tested) magnetization reaches considerable values before magnetostriction becomes perceptible. The apparatus used measures small changes in length so accurately that the data (cf. Table I)[1] establish this fact beyond question.

The theory demands that magnetostriction should begin in this way in all cases. For, at the beginning of magnetization only widely separated atoms are supposed to respond to the applied field. Although intense local stresses are set up about these oriented[3] atoms, the matrix of quite unmodified atoms offers to such local stresses an almost unyielding resistance. As, however, the continuity of the original structure is destroyed at more and more points, motion of the boundaries, with relief of accumulated stresses, occurs more and more readily.

The second thing to which attention will be directed is the curve in Fig. 5[1] showing the dependence of maximal magnetostriction upon the chemical composition (iron and nickel content) of unstretched permalloy. The second basic assumption of the theory is that atomic magnetostriction, i. e. the changes in the equilibrium positions of adjacent atom-centers due to changes in direction of the magnetic axis of the atom considered, are independent of the nature of the neighboring atoms. The theory views the greatest observable magnetostriction in any of these alloys as the net result of an expansion along the axis of magnetization, due to the orientation of all its iron atoms and a contraction along the same axis due to the orientation of all its nickel atoms. To a first approximation, therefore, the net magnetostriction should be a linear function of the concentration of either component (Fe or Ni). The approximation of the plotted points to a straight line justifies the second basic assumption of the theory.[4] The course of the curve suggests that face-centered cubic iron (as in austenitic steel) should, if it could be magnetically saturated, exhibit a magneto-

[3] An atom will be said to be oriented in a given direction when its magnetic axis is parallel to that direction, and to be unoriented when its magnetic axis has any other direction. It is not to be assumed that the magnetic moment of the unoriented atom is zero, and, as far as this paper goes, it is not necessary to suppose that the atomic magnetic moment is modified (except in the direction of its axis) by magnetic fields or other agencies.

[4] A second approximation calls for a defect from linearity in the magnetostriction-vs.-composition curve in the critical region, requiring nearly compensated alloys to show less expansion or contraction than that called for by the first approximation. There is some slight tendency for the points in Fig. 5[1] to deviate in this sense from the straight line there drawn.

strictive expansion greater than any magnetostrictive strain yet measured.

The smooth passage of the magnetostriction-vs.-composition curve through zero magnetostriction is in striking contrast to the abruptness of the changes in the magnetizability of stretched wires[5] in the same range of composition. This difference in the character of the two effects was to be expected, for, on general grounds,[6] the sensitiveness to strain should vary inversely as the magnetostriction, and where the latter passes through zero the strain-sensitivity should change discontinuously from its greatest positive to its greatest negative value. The observed variations in strain-sensitivity in the critical region are very great. That they are not infinite is not surprising in view of the unavoidable variations in local composition within a specimen of any alloy.

The third point of interest is the composition for which the net magnetostriction is zero. This can now be established as lying very close to 81 percent Ni, 19 percent Fe, and this is also the composition for which (in well-annealed alloys) hysteresis has its very low minimum value. The theory assumes that those groups of nickel and iron atoms in which atomic magnetostrictions are so compensated that hysteresis vanishes, are very small groups. If these groups were large the residuum of atoms left between groups organized at haphazard points within the alloy would frequently be ungroupable, and would give rise to considerable hysteresis even in that alloy for which the net magnetostriction is zero. The very low hysteresis observed in this alloy therefore substantiates the hypothesis of small groups.

The smallest group consistent with the critical composition thus indicated has four nickel atoms and one iron atom (80.6 percent Ni, 19.4 percent Fe). In a face-centered cubic solid solution the most compact and symmetrical arrangement of five atoms, four of one kind and one of another kind, is that in which the four like atoms form a rectangle lying in a (111) plane, with the fifth atom at its center. If a is the edge of the unit cube the sides of this rectangle are $a\sqrt{2}/2$ and $a\sqrt{6}/2$. A single iron atom completely surrounded by nickel atoms can be grouped in this fashion with four of its twelve neighbors in six different ways, so that even if it be essential to the proper functioning of such a group that the long edges of its rectangle lie nearly parallel to the applied field there is nevertheless a good chance of finding a suitably oriented group.

[5] Buckley, O. E., McKeehan, L. W., Phys. Rev. (2), **26**, 261–273 (1925).

[6] Kirchhoff, G., Berl. Ber. **47** 1155–1170 (1884).

While the hypothesis that this simple group is that in which atomic magnetostrictions are compensated is an attractive and tenable one in view of the present evidence, it cannot be considered proved. The important point at this stage is that a small group is required by the theory, and that a group of as few as five atoms (4 of Ni and 1 of Fe) will fit the observed critical composition.

The fourth problem which confronts the theory of atomic magnetostriction comprises the effects of tension on permalloys with notably more or less nickel than the critical amount (81 percent). These are the most interesting of the newly discovered facts, and they merit the most careful analysis (see Fig. 6[1]). In discussing the results observed in particular alloys it will be convenient to distinguish between atoms so grouped that all the atoms in a group become oriented (and magnetized) simultaneously, without magnetostriction or much energy loss, and atoms not so grouped. The former will be referred to as compensated atoms, the latter, as uncompensated. It is clearly the uncompensated atoms alone concerning which measurements of magnetostriction give direct evidence. Compensated atoms can only affect the results indirectly by offering resistance to the stresses set up around uncompensated atoms.[4]

It is to be kept in mind that there need be nothing essentially permanent about the grouping of compensated atoms. The same atom may, in different magnetic cycles, be compensated in one and uncompensated in another, depending upon chance variation of local conditions in the different cases. In any one case, however, the classification will be unique. The impossibility of predicting the classification of particular atoms will lead to no confusion in the present analysis.

In the permalloy wire containing 74 percent Ni tension diminishes the magnetostrictive expansion. It is clear that most of the uncompensated atoms in this alloy must be iron atoms. The theory says that the magnetic properties of the compensated atoms will not be affected by tension, and therefore that the observed change in magnetostriction must be due to something which affects the uncompensated (Fe) atoms alone. But the theory says just as positively that the atomic magnetostriction of iron (compensated or uncompensated) in face-centered cubic crystals cannot be altered, either in kind or in magnitude, by external agents such as tension. There is only one way of escape from this dilemma. The magnetostriction that occurs when a strong magnetic field is applied to a stretched demagnetized wire must be only part of the whole change in length producible by atomic orientation. Stretching the wire must, therefore, have oriented some of its atoms. It is found by direct experiment[5] that application of a strong field to a demagnetized wire produces the same change in magnetization with and without tension. Furthermore this change is half the change produced by reversing the field. These facts mean that in the magnetostriction experiments the initial magnetization is zero and the final magnetization has the same (saturation) value with and without tension. A little consideration shows that, if tension orients the same number of atoms in each of the two possible directions along the wire-axis, the whole change in magnetization when all are subsequently oriented in a single direction, will be the same as if the original state had been one of random orientation, as it is assumed to be in the annealed unstretched wire. The same invariance will not be shown by the magnetostriction, for the atoms oriented axially by tension have already contributed their quota to the change in length. Whether or not the applied magnetic field reverses their magnetic polarity the length of the wire is not altered. They are magnetizable but not magnetostrictive.

Precisely the same type of reasoning applies to the effect of tension on permalloy with 84 percent Ni. Tension orients the uncompensated (Ni) atoms transversely to the axis of the wire (but not all parallel to any particular diameter). Each atom so oriented should contribute a maximal quota to the magnetostriction later observed when strong fields produce magnetic saturation by orienting all the atoms parallel to the axis of the wire.

If sufficient tension can be applied to complete the axial type of orientation there will be no further change in length upon magnetizing permalloy with less than 81 percent Ni. In permalloy with more than 81 percent Ni, however, if complete transverse orientation can be produced by tension the characteristic contraction upon magnetizing should reach a limit somewhat greater than that in an unstretched specimen. That the limit should not be much greater is reasonable because the magnetostriction due to turning through 90° the axes of all the uncompensated nickel atoms, cannot be a large multiple of that due to turning them through angles ranging at random from 0° to 90°. The slope of a magnetostriction-vs.-composition curve plotted from data taken under any fixed tension should therefore change abruptly at the critical composition, being steeper on the high-nickel side. The broken line in Fig. 5[1] exhibits this effect of tension.

The effects of tension upon magnetizability[5] are also in agreement with this analysis. In the lower range of nickel content weak applied fields should suffice to reverse the orientation of uncompensated iron atoms which have, by tension alone, been oriented in the "wrong" direction. Atoms not oriented by tension alone should be oriented by weaker fields than if tension was absent. Both circumstances should raise the observed permeability and the first, in particular, should make the magnetization-vs.-field curves rise very abruptly. As far as compensated atoms are concerned the theory does not predict any change of behavior with tension. In the upper range of nickel content stronger fields should be required to orient axially the uncompensated Ni atoms which have, by tension alone, been oriented transversely. The range in stability of obliquely directed atoms should also be greater. Both circumstances should reduce the observed permeability and the magnetization-vs.-field curves under tension should rise less abruptly.

So far in this discussion it has always been assumed that magnetic fields have been applied to demagnetized specimens, so that the changes considered have been those taking place along the normal magnetization curve. The effects on hysteresis loops are simpler, for at saturation there are only two sorts of uncompensated atoms to consider, those oriented parallel to the applied field by tension alone and those so oriented under the cooperating (Fe) or opposing (Ni) effects of tension and applied field. In low-nickel permalloys, at sufficient values of the tension, only the first sort should be present, and reversal of their orientation should occur within a very narrow range of reversed magnetic field. The sharp corners and precipitous sides of the hysteresis loops corresponding to these conditions[5] are just what the theory demands. In high-nickel permalloys, on the other hand, only the second sort of uncompensated atoms are to be expected and the whole contour of the hysteresis loops under tension should be less angular, as experiment[5] shows it to be. In both cases, of course, the effect of uncompensated atoms is to be thought of as superposed upon the smooth but narrow hysteresis loop characteristic of compensated atoms, and best exhibited by permalloy with 81 percent Ni.[5] In low-nickel permalloys tension keeps iron atoms axially oriented so that the magnetic energy to be furnished for this purpose in each half-cycle is greatly diminished. The area of the magnetic hysteresis loop is correspondingly decreased. In high-nickel permalloys tension, whenever the applied field falls too low, orients nickel atoms transversely, wasting mechanical energy at the moment and requiring an extra supply of energy from the magnetic field to reorient the atoms axially at a later stage in the same half-cycle. The area of the magnetic hysteresis loop is correspondingly increased.

The mechanical nature of magnetic hysteresis, upon which the theory insists, is perhaps most evident in this type of experiment where a change in mechanical conditions alters magnetic energy losses.

The conclusions in regard to atomic orientation by tension are so novel that independent evidence on this point is highly desirable. Fortunately, such evidence exists. Experiments[7] in these laboratories have shown that the electrical resistivity of permalloy wires containing 78.5 percent Ni may be raised about as much (2 percent) by tension within the elastic limit as by magnetization to saturation, and that a combination of these causes produces no greater limiting change in resistivity than either cause alone. The theory of atomic magnetostriction suggests the following explanation for both sets of facts.

Change in resistivity in permalloy (at constant temperature) is due principally to atomic orientation and hardly at all to changes in dimensions (or distances between atom-centers). Magnetization and magnetostriction are due entirely to atomic orientation. In zero magnetic field tension produces atomic orientation equally in two opposite directions parallel to the tension—or, equally in all directions at right angles to the tension—and thereby produces change in resistivity and magnetostriction, but no measurable magnetizaton. Starting from any condition, the further change in resistivity producible by applying more tension or by increasing the applied magnetic field, and the further magnetostriction producible by increasing the magnetic field, measure the same thing, the extent to which the alignment of atomic axes (in uncompensated atoms) was incomplete at the start.

The fifth of the newly reported experimental results which will here be dealt with is the reversal in magnetostriction in stretched permalloy containing 80 percent Ni (Fig. 6[1]). This alloy is, on the average, so nearly compensated that the composition in small regions may lie on either side of the critical composition. Uncompensated atoms of both iron and nickel should therefore be present in the specimen. In the unstretched alloy it is experimentally evident that in the first stages of the process of magnetizing the net magnetostriction is zero, so that the uncompensated atoms, if oriented at all during this stage, must be oriented in nearly the compensating ratio. This quasi-compensation is different from the true compensation previously defined, in depending on events non-adjacent in time or in space, and should not therefore entail abnormally low hysteresis losses. It is also different from true compensation in being upset by tension, because tension orients and disables from subsequent magnetostrictive action a large fraction of the

[7] Arnold, H. D., McKeehan, L. W., Phys. Rev. (2) **23**, 114 (1924).

uncompensated iron atoms, leaving the uncompensated nickel atoms to control the observed magnetostriction in low fields, and enhancing their average contribution thereto in the manner already described. It is apparent that with tension sufficient to orient all uncompensated iron atoms the only observable magnetostriction should be a contraction. In the case examined the tension was not so great as this, and a final expanson of small amount betrays the presence of uncompensated iron atoms not oriented by the applied tension alone.

The experiments of Webster[8] on magnetostriction in single iron crystals show that even in these simplest of structures magnetic processes are quite analogous to those in crystal aggregates, upon the behavior of which the theory of atomic magnetostriction has been based. This is not surprising, because even the smallest crystal in an annealed aggregate contains so many atoms that inter-atomic actions should be practically independent of crystal size. (Intra-atomic actions are, by definition, independent thereof.) The dependence of magnetostriction upon direction of magnetization is, in the body-centered crystals studied by Webster, very complicated. In explaining magnetostriction in the aggregates of face-centered crystals examined by McKeehan and Cioffi[1] it has not been found necessary to assume different magnetostrictive properties in different directions within each crystal. The study of magnetostriction in single nickel crystals would be of great interest in this connection.

The equivalence of tension and magnetic fields in orienting ferromagnetic atoms supplies a clue to the nature of the "molecular" field postulated by Weiss[9] to account for magnetic retentivity. The more or less random stresses in ordinary metals would, in accordance with the views here expressed, do that for which this molecular field was evoked, for they would in the case of all but favorably oriented atoms tend to maintain the established direction of magnetization against small disturbances, and thus confer upon magnetization that stability which the simple interaction of freely turning magnets cannot furnish. The development of specialized atomic orientation by tension also requires in ferromagnetic metals, far below the elastic limit, a defect of proportionality between stress and strain, a dissipation of energy as in magnetic hysteresis, and the same opportunities for lag and aftereffects that occur in such changes of atomic orientation as can be followed by magnetic measurements alone. Mechanical hysteresis in

[8] Webster, W. L., Proc. Roy. Soc. **109A,** 570–584 (1925).

[9] Weiss, P., J. de phys. (4) **6,** 661–690 (1907); Ann. de physique (9) **1,** 134–162 (1914); Arch. des sci. (4) **37,** 105–116, 201–213 (1914); (5) **6,** 417–418 (1924).

ferromagnetic metals (except in permalloy with 81 percent Ni) should therefore be abnormally high.

Conclusion

The theory of atomic magnetostriction is found to suggest an adequate explanation for magnetostriction in permalloy and establishes a close correspondence between magnetostriction and the changes in resistivity which accompany magnetization and tension. It suggests that the orientation of the magnetic axes of ferromagnetic atoms may be affected by mechanical as well as by magnetic forces, makes more rational the molecular field postulated by Weiss, and should prove useful as a guide in attacks upon unsolved problems in ferro-magnetism.

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