THE MAGNETOSTRICTION OF A MAGNETITE CRYSTAL

By C. W. Heaps

Abstract

Magnetostriction of an octagonal magnetite crystal along three axes was measured in fields up to 5000 gauss. The curves obtained are all similar in form, first convex towards the H axis, then concave, tending toward a maximum near 5000 gauss. With a longitudinal field of 5000 gauss, the digonal axis expands $30(10)^{-4}$ per cent, the trigonal axis $12(10)^{-4}$ per cent, and the tetragonal axis contracts about $4(10)^{-4}$ per cent. With an equal transverse field the percentage changes are a contraction of $44(10)^{-4}$, a contraction of $28(10)^{-4}$ and an expansion of $4(10)^{-4}$, respectively. Tests indicated that the effect perpendicular to a plane is independent of the direction of the field in that plane. No departure from cubic symmetry was established. To explain these results a *model of the magnetic element* in magnetite is suggested, similar to Ewing's recent model. The experiments favor the view that the rotating magnetic element is a group of non-parallel electron orbits inside the atom.

Permeability of a magnetite crystal was roughly determined to vary from 1.2 to 1.38 as the field strength increased to 5000 gauss.

In a recent paper[1] the writer described some magnetostrictive effects obtained with a crystal of magnetite ground into the form of a sphere. The experiments, however, were not of a definite enough nature to permit the exact correlation of the magnetostriction with the directions of the crystallographic axes. The great differences in the character of the phenomena for different directions in the sphere made the location of these axes with respect to the magnetostriction a matter of some importance. Further experiments have now been performed and the magnetostriction definitely correlated with the axes.

The apparatus for measuring dimension changes, except for a few modifications made in order to facilitate the adjusting of the specimen, was the same as described in the previous paper. An electromagnet smaller than the one of the previous experiments was used in this later work. It had pole-pieces 5.8 cm in diameter and these were kept 3.3 cm apart throughout the work. The field, therefore, was probably not as uniform as in the case of the larger magnet. Tests with a flux-meter and search coil showed the field midway between the pole-pieces to be somewhat less than 2 per cent smaller than the field very near the pole-pieces.

The magnetite crystal was an octahedron from Henry County, Virginia. It was quite perfect, with principal axes about 1.8 cm long. Before

[1] Heaps, Phys. Rev. **22**, 486, 1923

making measurements on this crystal the corners and edges were rounded off by grinding. It was thus easier to clamp the crystal in the measuring device; also the specimen was made more nearly spherical and the intensity of magnetization presumably more uniform.

Magnetostriction of the specimen was investigated with respect to three different crystallographic axes, the tetragonal, the trigonal, and the digonal. Magnetite belongs to the cubic system, the eight faces of the octahedron being equilateral triangles. The three fundamental axes of the cube, the tetragonal axes, join opposite vertices of the octahedron. The four trigonal axes, each of which connects opposite vertices of the elementary cube, have the direction of the normals to the faces of the octahedron. The six digonal axes are each perpendicular to a pair of parallel edges of the octahedron.

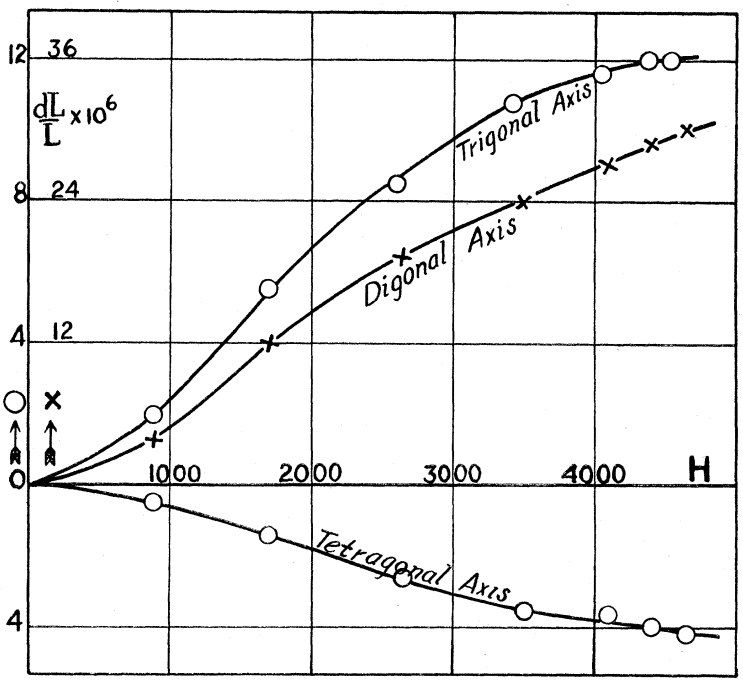

Fig. 1. Longitudinal magnetostriction along different axes.

The curves of Fig. 1 represent the magnetostriction obtained in the direction of the field for different values of the magnetic field H (measured in the absence of the crystal). Here dL/L is the change of length of an axis divided by the total length of that axis. The longitudinal magnetostriction along the digonal, trigonal, and tetragonal axes varies in much the same way with the field as the latter is increased, but the contraction

(plotted below the H axis) along the tetragonal axis is smaller than the expansions (plotted above the H axis) which occur for the same fields along the trigonal and digonal axes. It is to be noted that two scales are used, the curve for expansion of the digonal axis being plotted with reference to the scale giving the larger values.

Fig. 2 gives the magnetostriction along three different axes, the field being for each curve normal to the axis specified on the curve. Contractions are plotted below the H axis, expansions above the axis. It appears

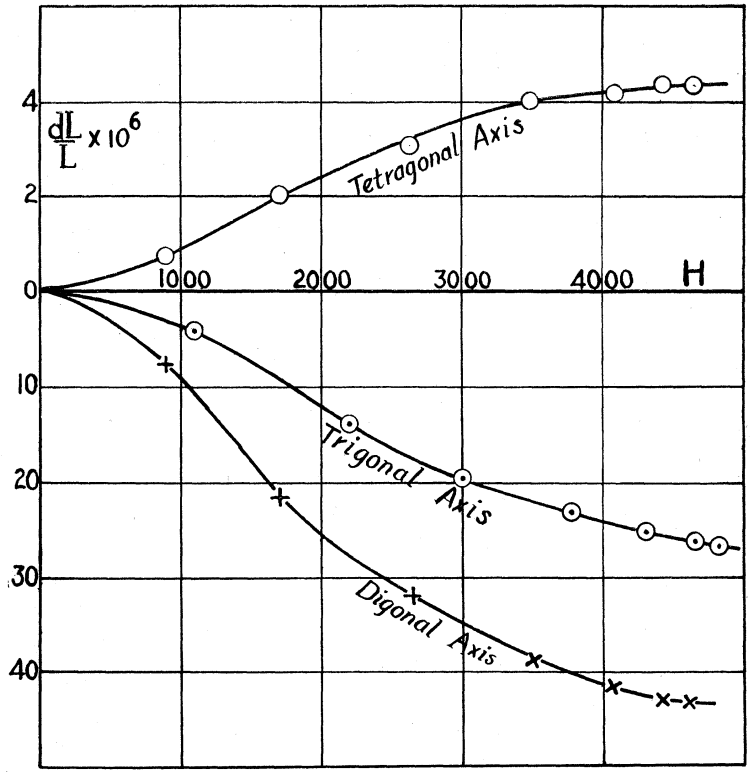

Fig. 2. Transverse magnetostriction along different axes.

that for transverse magnetic fields the tetragonal axis expands while the trigonal and digonal axes suffer contractions of considerably larger magnitudes.

The curves of Figs. 1 and 2 are all similar in appearance. They are also similar to the curves for a magnetite sphere which are given in the previous paper. The curves for the sphere, however, are plotted against magnetic induction and are extended to higher values of the field so that the existence of maxima is more clearly indicated than in Figs. 1 and 2.

The field instead of the induction is plotted in the present work because of the difficulty of measuring the latter quantity accurately when the specimen is not spherical. Approximately correct values were obtained, however, by using a fluxmeter connected to five turns of wire wound around the specimen. In this way the permeability of the magnetite was found to vary from 1.2 to 1.38 for the field values plotted in the curves.

In its magnetic properties magnetite has been found[2] to show departures from cubic symmetry. To investigate this question the transverse magnetostriction for the different tetragonal and trigonal axes was measured. It was found that slight departures from accuracy in the setting of the crystal caused considerable changes in the magnitude of the magnetostriction so that small deviations from cubic symmetry could not be detected easily. It seemed possible, however, that one of the tetragonal axes expanded more than the others under the influence of the field.

From the curves of Figs. 1 and 2, and on the assumption of cubic symmetry, the curves of Fig. 3 were constructed. Here the maximum magnetic field is supposed to be rotated in one of the planes of symmetry of the crystal, the angle θ between the tetragonal axis and the field being plotted as abscissas, the corresponding magnetostriction as ordinates. From these curves it appears that a longitudinal field rotated in the axial plane (100) produces two maxima of extension and two maxima of contraction in a half revolution, the contractions being small compared with the expansions. When the field is rotated through 180° in the (011) plane only one maximum of expansion and one of contraction are obtained.

For the transverse field rotated in these same two planes the magnetostriction at right angles to the field is taken in the plane of rotation. The curves are similar to those for the longitudinal field except that there is an interchanging of contraction and expansion. If a crystallographic axis expands in a longitudinal magnetic field it contracts by about the same amount when turned transverse to the field; or if it contracts in the longitudinal field the transverse field will make it expand by about the same amount.

A number of experiments were made to see whether the magnetostriction perpendicular to a given plane varied with the direction of the field in this plane. The transverse field was found to produce the same expansion of a given tetragonal axis (within the limits of error of the experiment) when directed along one of the perpendicular tetragonal axes as when parallel with one of the perpendicular digonal axes. Ap-

[2] Kunz, Bull. Nat. Res. Council, **3**, 177, 1922

parently, therefore, rotation of the field in the (100) plane does not change the magnitude of the magnetostriction normal to this plane. Further experiments made it seem probable that the magnetostriction normal to the (011) plane and to the (111) plane is unaltered by rotating the field in these respective planes.

Discussion of Results with Reference to Theories

In the previous paper it was suggested that Ewing's recent model of the magnetic atom could be made to fit in with magnetostriction phenomena. The present experiments seem to impose the following conditions on this model in magnetite:

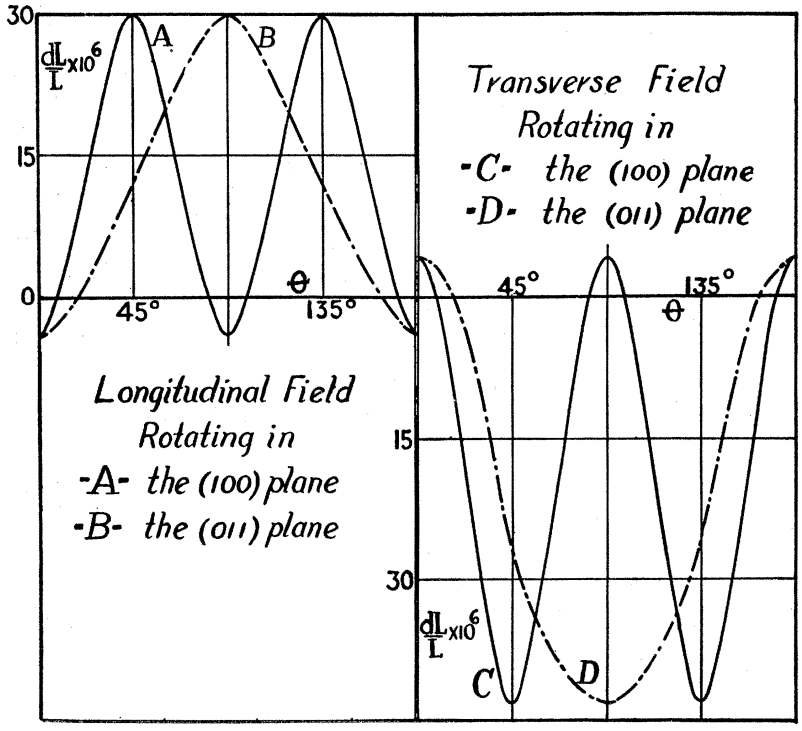

Fig. 3. Magnetostriction for different directions in given planes.

1. In one complete rotation of the Weber element in the (100), (010), or (001) planes it passes through four positions of maximum force which tend to expand the crystal and four positions of maximum force which tend to contract it. This force is presumably exerted by the Weber element either on the outer parts of its own molecule or on neighboring molecules. In the former case it must be supposed that the molecule is

strained and that the straining of the molecules alters the distances between their centers.

2. The Weber element must possess laterally a mechanism for producing the same type of force changes as are produced longitudinally.

3. The Weber element, or the rotating mechanism, must be confined to the inner part of the molecule. Otherwise a magnetic field, by rotating the outer parts of the molecules, could produce changes in those properties of the crystal, such as cohesion, etc., which depend on the outer parts of the molecules, and the crystallogrpahic axes could have their directions changed by means of a magnetic field.

The following modification of Ewing's model will satisfy the above conditions. Let the fixed outer portion of the molecule be represented by a cube with twelve magnets fixed respectively to the center of each edge, the north pole of each magnet being directed inwards and the axes of the magnets being supposed to lie along the digonal axes of the cube. The rotating element may consist of a similar cube centered within the first, the magnets of the inner cube having their south poles directed outwards towards the north poles of the outside cube. An externally applied field must exert a directive influence on this cube; also the longitudinal magnetostrictive effects are the converse of the transverse effects. Hence it is necessary to assume that one pair of magnets, with axes on the same line, have their north poles protruding, and one of these two north poles is slightly stronger than the other.

Fig. 4 gives a diagram of the model. Here the inner rotating cube is considerably simplified for the sake of clearness. Only the magnets are shown, and each of the poles marked Σ is supposed to take the place of four south poles making angles of 60° with each other. The poles of the Weber element in the position shown are supposed to lie very close to the planes of the outer cube in which the north poles are situated. These latter poles are represented by circles. In the diagram, if N' is stronger than N the external field may be supposed directed along Ox.

Magnetostriction can occur as follows: In the position shown each pole marked S will attract those north poles of the plane in which it lies. The two Σ poles will exert attractive forces on all the poles of the external shell, the compressive force being less along the direction Oz than along the other two axes. The poles N and N', lying approximately in the two yOz planes of the diagram, will exert repulsive forces on the north poles of these respective planes. Hence all the forces named tend to produce contraction in the direction of the field, that is, along the tetragonal axis of the crystal. Expansion in transverse directions would

result if the repulsive effects of the N and N' poles exceed the other attracting forces.

It seems probable that the action of the Weber element on similar elements in neighboring molecules should be considered. In this case contraction in the direction of the field would result provided the following condition is satisfied along Ox: compressive force of S poles + compressive force of Σ poles > expansive force of N and N' acting on the N' and N poles of neighboring elements. To produce transverse expansion, along Oz for example, we must have for this direction: compressive force of S poles + compressive force of Σ poles < repulsive force of N and N'+ repulsive force of Σ poles on the Σ poles of neighboring elements. In Fig. 4 the inner system is shown in a position which would not

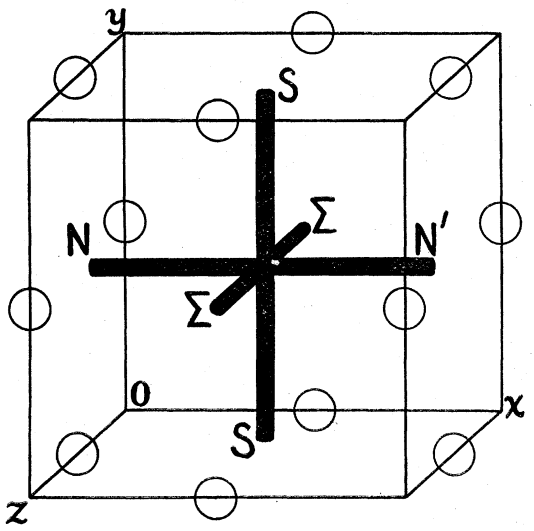

Fig. 4. Model of the magnetic element in magnetite.

be stable when forces exist between the different systems. For stability under these conditions the Weber element must be rotated slightly about the Ox axis. However it is possible in the rotated position to explain magnetostriction in the same way that it is explained above. When the field is directed along the digonal axis of the cube a large expansion in the direction of the field is to be expected and a similar large contraction transverse to the field, because in this case each pole of the Weber element is directly under a pole of the outer shell.

If the influence of neighboring atoms is to be considered in the fashion outlined above it is obviously of importance to know the crystalline

structure of magnetite in detail. W. H. Bragg[3] has analyzed this mineral and found it to have a space lattice similar to that of diamond. The (100) planes consist of Fe_2O_4 planes having the spacing 2.07 A interleaved with Fe planes. The (110) planes consist of Fe_2O_2 planes 2.94 A apart interleaved with FeO_2 planes. The (111) planes are Fe planes 4.8 A apart interleaved with several iron and oxygen planes. On the average it appears that the (110) planes have the largest spacing; it is also these planes which experience the greatest normal displacements under the influence of parallel or normal fields. It is possible that the greater spacing of these planes gives them greater freedom of motion. The weaker forces of the Weber elements on each other across the greater interplanar distance does not appear to be of importance in the model suggested above, since it is assumed practically negligible in this direction.

This model of the magnetic atom of magnetite is to be considered merely as suggestive. When the magnetostriction of a pure iron crystal has been investigated it may be possible, knowing the space lattice of magnetite, to devise a much more satisfactory model. The one suggested, however, agrees with the concentric shell theory of the atom and it meets the demand that the rotating element should be only a small part of the atom. On modern theories of atomic structure the magnets of this model would naturally be replaced by electron orbits. In this case there is objection to the model on theoretical grounds, since for stability it appears that the orbits should be coplanar. It is entirely possible that a Weber element could be devised with parallel magnets and that this element could be made to give the magnetostriction found experimentally. However, the assumptions regarding the nature of the forces do not appear to be simple enough. The approximate equality of the magnitudes of the transverse and longitudinal magnetostrictions suggests similar mechanisms for the production of the effects. It seems natural, therefore, to suppose that if aligned north poles produce longitudinal expansion then south poles aligned in this same direction produce the transverse contraction. Thus magnetostriction phenomena in magnetite favor the view that the magnetic element is a group of electrons rotating in orbits which are not parallel with each other. This group is probably one of the inner shells of the atom.

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[3] W. H. Bragg, Phil. Mag. **30**, 305 (1915)