The Effect of Strain on Magnetostriction and Magnetization in Nickel

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With a heterodyne beat method, magnetostrictive hysteresis loops have been obtained for a nickel wire under three different tensions. Magnetic hysteresis loops for the same wire and same tensions were also secured. The magnetostrictive contraction, dL/L, for the tensions 6.82 and 3.70 kg/mm^2 is given quite accurately by the one equation, $dL/L = -1.93\times 10^{-10}\ I^2$, where I = intensity of magnetization. For a tension 0.72 kg/mm^2 the equation $dL/L = -1.30\times 10^{-10}\ I^2$ holds somewhat less accurately. The effect of compression and of stretch on the residual magnetization of a nickel wire in a demagnetizing field is determined experimentally. From this experiment, and from the magnetostriction curves, it is shown that at certain field strengths the magnetism of a nickel wire, bent elastically into a circular arc, becomes unstable. Thus the large discontinuities in the magnetization curve observed by Forrer may be explained. It is suggested that the small Barkhausen jumps of magnetization may be due to similar magnetic instability produced in small regions by local strains.

THE phenomenon of hysteresis in magnetostriction has been observed by a number of investigators,[1] but a detailed study of the effect of strain on magnetostrictive hysteresis does not appear to have been made. The importance of strain, both in theories of magnetism and in experiments on particular phases of the subject, has recently been emphasized; for example, the very great influence which strains in the material may have on the Barkhausen effect or on the magnetic hysteresis loop.

The present paper reports experiments in which the magnetostrictive hysteresis loops and the magnetic hysteresis loops have been determined for a nickel wire under different tensions. Nickel was chosen for the experiments because the magnetostriction curves of a nickel crystal are not greatly affected by the orientation of the crystalline axis;[2] hence in a polycrystalline wire the effect of crystal size or crystal orientation should be of little importance in modifying magnetostriction. Furthermore, it is in nickel that very striking discontinuities of magnetization have been produced by strains in the material.[3] The explanation of these discontinuities was one of the objects of the experiment.

The Experimental Method

For observing magnetostriction the heterodyne beat method of measuring small capacity changes or small displacements was used. Two oscillating elec-

[1] H. Nagaoka, Phil. Mag. [5] **37,** 131 (1894); L. W. McKeehan, J. Franklin Inst. **202,** 737 (1926); A. Schulze, Ann. d. Physik [5] **11,** 937 (1931); G. Dietsch, Zeits. f. techn. Physik **12,** 380 (1931).

[2] Y. Masiyama, Sci. Rep. Tohoku Imp. Univ. [1] **17,** 945 (1928).

[3] R. Forrer, J. de Physique [6] **7,** 109 (1926); **10,** 247 (1929).

trical circuits have their beat note (of audiofrequency) picked up by a detector, amplified, and impressed upon an oscillograph. One plate of a condenser in one of the oscillating circuits is supported by the nickel wire under test. This wire is surrounded by a solenoid. If the field in the solenoid is varied the length of the nickel wire changes, thus changing the capacity of the oscillating circuit. The frequency of the heterodyne beat note is therefore altered by an amount which can be determined from the oscillograph record. From a knowledge of the calibration constant of the apparatus the change of length of the wire may thus be calculated. Details of the electric circuits have been described elsewhere.[4]

Fig. 1 shows the arrangement of the condenser, the capacity of which is changed by the magnetostriction of the nickel. This condenser is connected in parallel with an adjustable precision condenser which was set to have the same large capacity throughout the experiment. The upper plate B has a

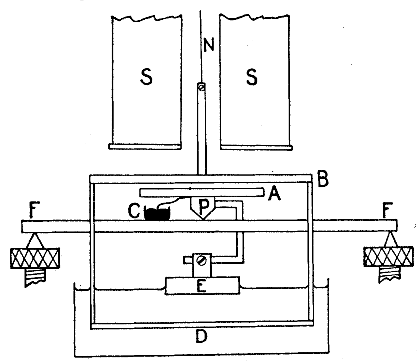


Fig. 1. Arrangement of condenser in the magnetostriction apparatus.

diameter 5 cm and is connected to earth through the nickel wire N. Three light, vertical rods, of which two are shown, are fixed to the edge of the upper plate and support a flat ring D of aluminum, immersed in oil to serve as a damping fluid. Plate A, of diameter 2 cm, is insulated by Bakelite from the point support P and counterbalance E. A wire from this plate dips into the mercury cup C by means of which connection is made to the oscillating circuit.

The micarta cross-bar FF, is supported on three leveling screws, of which two are shown. These screws are used to vary the capacity of the condenser. The plate A is carefully leveled by adjusting the counterweight E, which also serves as a damping plate. Weights may be placed on top of B to produce tension in the wire N. To level B accurately a small, easily movable weight was carefully adjusted on the top of the plate.

The solenoid, SS, of which only the lower part is shown, is 30.3 cm long and has 7195 turns. It is supported on a stand separate from that which supports the wire N. The nickel wire is 15 cm long and 0.018 cm in diameter. It is carefully centered in the solenoid so as to be in a uniform field. The current through the solenoid may be given a series of values by opening or closing a

[4] A. B. Bryan, Phys. Rev. [2] **34,** 615 (1929); C. W. Heaps and A. B. Bryan, Phys. Rev. [2] **36,** 326 (1930).

series of switches which short circuit sections of a rheostat. These switches consisted of a series of metal contacts spaced equally along a vertical micarta bar which could be pushed down into a jar of mercury. With this device it was possible to put the nickel wire through the entire hysteresis loop in only a few seconds, the successive changes of length being indicated by frequency changes on a section of oscillograph film about 10 feet long. A condenser in series with a heavily damped vibration galvanometer was connected across the switching device, so that every time the solenoid current changed, the galvanometer received an impulse which was recorded on the oscillograph film.

The oscillograph consisted of a telephone receiver to the diaphragm of which a light mirror was connected. Records were obtained on positive motion picture film and developed by the contrast developer recommended by Town.[5] The time scale was obtained by interrupting a beam of light by the cogs in the wheel of an electric clock running on 60-cycle current. Fig. 2

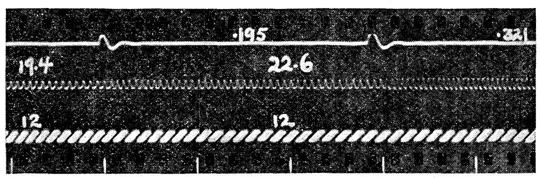


Fig. 2. Oscillograph record. Top trace = solenoid current; middle trace = heterodyne note; bottom trace = time scale.

shows a section of film. The topmost trace indicates changes of current in the solenoid, the middle trace is a record of the heterodyne beat note, the bottom trace is the time scale, each segment representing 1/60 sec. The figure shows how the film was marked and how the frequency was determined for a given value of the magnetizing current.

To convert frequency changes into length changes it was necessary to calibrate the device. The following method was used. A leveling screw at F was adjusted till the heterodyne beat note emitted by the telephone receiver was in accurate tune with a tuning fork of pitch 1024. A micrometer microscope was then focussed on a fine scratch on plate A. By means of the leveling screw the plate A was now moved either up or down, so as to lower the pitch of the heterodyne note down through zero frequency and up to the frequency 1024 again. A total frequency change of 2048 was thus secured and the motion of A was large enough to be measured with considerable accuracy. For very small displacements of A (or B) such as were used in the experiment, it may be shown that the frequency change of the heterodyne note is proportional to the displacement. Thus the length change of the wire per cycle of frequency change is easily calculated. Throughout the experiments the value of this quantity was kept at 2.10×10^{-6} cm per cycle.

Magnetic hysteresis loops were secured by using a sensitive astatic magnetometer of the type described by Bozorth.[6] The vertical component of the

[5] G. R. Town, Rev. Sci. Inst. **1,** 449 (1930).

[6] R. M. Bozorth, J.O.S.A. and R.S.I. **10,** 591 (1925).

earth's magnetic field was neutralized by means of Helmholtz coils, both in the magnetometer experiments and in the magnetostriction experiments. Demagnetization of the nickel could be effected by using liquid rheostats to decrease a 60-cycle alternating current through the magnetizing solenoid.

The nickel wire was cold drawn from Eimer and Amend's *pure sheet nickel.* After the drawing the wire was heated electrically to a bright red in an atmosphere of carbon dioxide, and cooled slowly by gradual decrease of the heating current. It was loaded and unloaded several times up to the limiting tension used in the experiment before any records were taken. The wire was very soft and experiments on a short sample indicated a definite yield at about 14 kg per mm². In order to keep well within the elastic limit stresses greater than 7 kg per mm² were not used during the experiment.

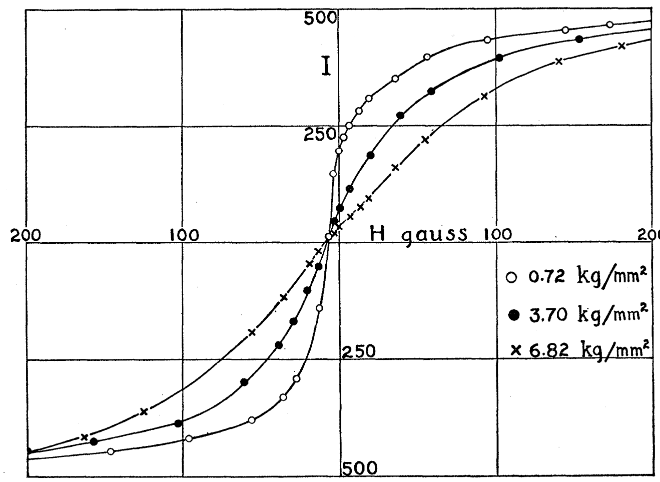


Fig. 3. The effect of tension on the descending branch of the hysteresis loop of nickel.

Discussion of Results

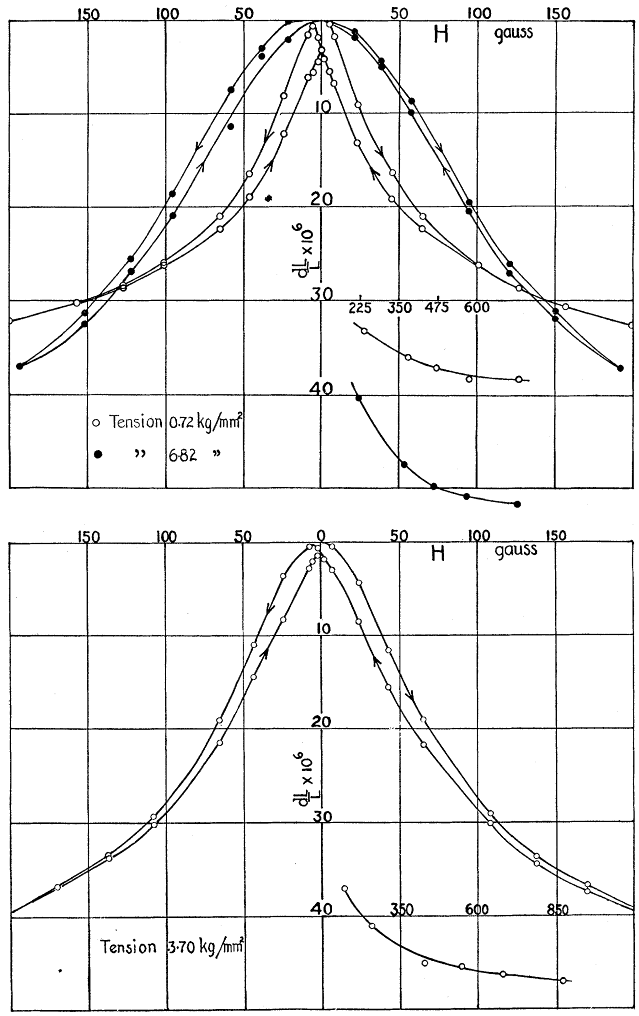
Fig. 3 shows how tension affects the magnetic hysteresis loop. These results agree, in general, with previous work.[7] Figs. 4 and 5 show the effect of tension on magnetostriction. A point of interest here is the fact that the curves for different tensions cross at large values of the magnetic field, *H*. In other words, it appears that tension applied to a nickel wire will decrease the magnetostriction in small fields and increase it in large fields. Bidwell[8] has observed a similar phenomenon. The explanation, as will appear later, lies in the way in which the intensity of magnetization varies with the field strength.

A second point of interest in connection with these curves is the effect of strain for very small fields. When the wire is loaded with 6.82 kg/mm² and saturated magnetically, the residual magnetostriction when the field is

[7] M. Kersten, Zeits. f. Physik **71**, 553 (1931).

[8] S. Bidwell, Proc. Roy. Soc. **47**, 469 (1890).

brought to zero is too small to be detected. Furthermore, a reverse field of at least 20 gauss must be applied before the magnetostriction becomes large enough to measure. The conditions are quite otherwise when the wire carries only 0.72 kg/mm². In this case the residual magnetostriction is quite large,



Figs. 4, 5. Fractional change of length, dL/L as a function of magnetic field, H. The short segments are extensions to large fields.

and the reverse field, as it increases, causes the wire to elongate[9] till a field of about 6 gauss is reached. At this point the residual magnetization is re-

[9] This elongation, of course, is really a diminution of contraction produced by a decrease of residual magnetization. Deitsch (reference 1) appears to consider it as actual positive magnetostriction of nickel. There seems to be little doubt, however, but that it may be accounted for in the work of Dietsch by incomplete demagnetization of his specimen. In such a case the origin of the magnetostriction curve is improperly located.

duced to zero and for further increase of field the wire contracts. As will be noted later, this difference of behavior of stretched and unstretched nickel is of special significance in relation to discontinuities of magnetization.

In Fig. 6 the magnetostriction is represented as a function of the intensity of magnetization. The plotted points are values taken from the curves of Figs. 3, 4, and 5. The line drawn through the points and designated by A is the graph of the equation $dL/L = -1.93\times 10^{-10}\ I^2$. It appears that for the two tensions, 3.70 and 6.82 kg/mm^2, the one curve A represents the experimental results with considerable accuracy. It is somewhat surprising that an increase of tension from 3.70 to 6.82, which produces such marked changes in the magnetic hysteresis loop and in the magnetostriction loop as plotted against the magnetic field H, should really have no effect on magnetostriction considered as a function of I.

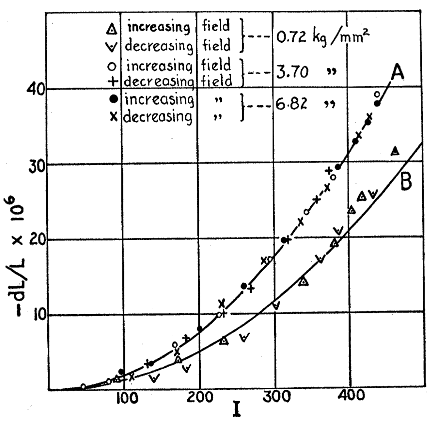


Fig. 6. Magnetostriction as a function of intensity of magnetization.

For the smallest tension the plotted points[10] are somewhat irregularly distributed. The curve drawn through these points and designated by B is the graph of the equation $dL/L = -1.30\times 10^{-10}\ I^2$. It represents to a fair approximation the experimental results. However, for small values of I the plotted points indicate the existence of appreciable hysteresis. The work of McKeehan and Cioffi, and of A. Schulze, seems to show that hysteresis is present in the $dL/L-I$ curves for unstrained nickel, in agreement with the present work. From Fig. 6, curve A, the additional conclusion may be drawn that the application of sufficiently large strains makes this hysteresis effect negligibly small.

Recently some important theoretical work has been done on the subject of magnetostriction. The theories of Akulov[11] and of Becker,[12] in which the energy of a strained dipole lattice is taken as the starting point, have been shown by Powell[13] to be consistent with each other. Powell's equation for

[10] The points for this curve are obtained on the assumption that $dL/L=0$ when $I=0$.

[11] N. Akulov, Zeits. f. Physik **52,** 389 (1928); **59,** 254 (1930); **64,** 817 (1930); **69,** 78 (1931).

[12] R. Becker, Zeits. f. Physik **62,** 253 (1930); **64,** 660 (1930).

[13] F. C. Powell, Proc. Camb. Phil. Soc. **27,** 561 (1931).

dL/L makes the effect proportional to I^2. Powell states that his equation need not necessarily apply to values of dL/L determined experimentally because of the possibility of micromagnetization of crystals which as a whole are unmagnetized. In spite of this limitation it appears that where tension is applied to nickel the theoretical law of variation of dL/L is verified experimentally to a considerable degree of accuracy.

We may now consider why curve A of Fig. 6 represents equally well the data for the two large tensions. The obvious explanation is that either of the two large tensions is sufficient to produce a saturation effect. When tension is applied to nickel, current theories[14] agree in supposing that the atomic magnets are orientated across the axis of tension, or that the magnetization vectors, I, of small microscopic blocks into which the nickel is divided, are so orientated. For a sufficiently large tension there is complete transverse orientation. A longitudinal magnetic field, in order to magnetize the wire to saturation, must orientate all these atomic magnets along the axis of the wire, thus causing maximum magnetostriction. When no tension is applied the atomic magnets may be initially orientated at random and the magnetic field, in lining them up, cannot produce such a large net length change because of the less favorable initial distribution of axes.

It appears from the curves of Fig. 6 that tensions of 3.70 and 6.82 kg/mm^2 are equally effective in producing complete transverse orientation of atomic magnets in nickel. This conclusion may be drawn because for both of these tensions we get the same magnetostriction produced by a given intensity of magnetization. On the other hand, for the tension 0.72 a considerably smaller magnetostriction is produced by this same intensity of magnetization. It is probable that the atomic magnets of the nickel under the tension 0.72 are distributed more or less at random. There will not be completely random orientation, however, even with this small tension. The quantitative working out of the theory indicates that the maximum magnetostriction under large strain should be 1.5 times the maximum magnetostriction under no strain. This ratio for tensions 6.82 and 0.72 is only 51.8/38.3, or 1.35. Apparently, therefore, the small strain has produced an appreciable transverse orientating of atomic magnets.

The Effect of Strains on Residual Magnetism

The curves of Fig. 3 do not give a complete picture of the processes which may occur in the region of demagnetization. For example, from these curves, each obtained at constant tension, it might be concluded that compressing nickel in a demagnetizing field would increase the residual magnetism. However, since shock and vibration are known to facilitate demagnetization there might be some doubt about the correctness of this conclusion. In order to secure more detailed information regarding the region of demagnetization the following experiment was performed.

A wire of commercial nickel, 15 cm long and about 1 mm in diameter, was soldered to a strip of brass 15 cm long, 0.16 cm thick, and about 3 cm wide.

[14] L. W. McKeehan, reference 1; R. Becker and M. Kersten, Zeits. f. Physik **64**, 665 (1930).

The wire was soldered throughout its length to the brass and was parallel to the strip's long dimension. The brass strip was then suspended in a vertical solenoid beside the magnetometer, a second solenoid being arranged to balance the field of the first solenoid at the magnetometer. The effect of the magnetized nickel on the magnetometer could also be balanced by a third small solenoid. By bending the plate in one direction the nickel wire was stretched, by bending it in the opposite direction it was compressed. Furthermore, by clamping the strip with an initial bend, adjusting the demagnetizing field to the proper value, and then altering slightly the amount of bend, the effect of this small change of strain on the value of I could be determined by observing the direction of deflection of the magnetometer.

Fig. 7 gives qualitatively the results of the various experiments. Curve A is representative of compressed nickel, curve B of stretched nickel. The

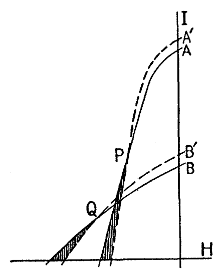


Fig. 7. The effect of strain on the intensity of magnetization of nickel in a demagnetizing field.

stretched wire has a smaller residual magnetism and a larger coercive force than the compressed nickel. The dotted curves associated with A and B indicate the effect of increasing the compression in each case.

The shaded areas represent regions where irreversible effects occur. In one case when the nickel was in a state of compression the point P was at about 8 gauss. For fields less than 8 gauss an increase of compression caused a reversible increase of residual magnetism. (However, as P was approached there was a decided tendency for irreversible decreases of magnetism to occur when the excess compression was removed.) For demagnetizing fields greater than that at P an increase of compression always caused an irreversible decrease of I. On the basis of these results the dotted curve A' was drawn as in Fig. 7.

It was found that in demagnetizing fields greater than that at P a decrease of compression produced an irreversible decrease of I. Hence the shaded area cannot be entered vertically starting from the dotted curve A'; any attempt to enter in this way results in a drop downwards.

Very similar results were obtained with nickel when initially in a stretched condition, the curves B and B' being obtained. In one case the point Q was at about 10 gauss.

Discontinuities of Magnetization

If a nickel wire is subjected to a bending torque its magnetization curve shows remarkably large discontinuities.[15] For the production of these discontinuities it appears necessary that part of the wire be in a state of compression and part in a state of tension. If a wire with no internal strains is bent into the arc of a circle and the elastic limit not exceeded, we probably have the simplest conditions for producing these large discontinuities. In this case we may make a rough approximation and consider the wire as behaving like two wires fastened together laterally, one wire being stretched, the other compressed. The magnetic and magnetostrictive behavior of these separate wires is known from experiment, hence the behavior of the composite wire should be predictable.

Assume the composite wire magnetized to saturation in one direction and then subjected to a gradually increasing field in the opposite direction. For small values of this field we may assume from Fig. 4 that there is negligible magnetostriction of the stretched component. The compressed component of the composite wire will increase its length as the field increases. This increase of length of the compressed section tends to increase the degree of compression, since the wire will be assumed not to bend. Also, the tension of the stretched section is increased. The situation is similar to that found where a straight, bimetallic strip is used on a thermostat. As the temperature rises and the strip is not allowed to curve, one metal is increasingly compressed, the other increasingly stretched.

It is easy to show that the magnetization of such a composite wire will be stable for demagnetizing fields less than those corresponding to points P or Q, Fig. 7. In demagnetizing fields greater than these, however, there is instability. For, consider a small increase, ΔH, occurring in a shaded region of Fig. 7, and assume outside forces applied so as to keep the tensions in the two parts of the composite wire constant during this change. We then get decreases, ΔI_A, and ΔI_B, respectively, in the magnetizations of the compressed and stretched segments. However, from Figs. 3 and 7 we conclude[16] that ΔI_B is much smaller than ΔI_A. Also from Fig. 4 we see that ΔH in this region produces negligible length change in the stretched segment B, as compared with that in the compressed segment A. Since the composite wire is not allowed to curve, the increase of length of A would produce a compressive stress in A and a tension in B, were it not for the external forces assumed to be applied. These forces are a pull on A and a compressive stress on B. Now remove these outside forces. From Fig. 7 it appears that decreases of magnetization, δI_A and δI_B, result, the value of δI_B being much less than δI_A. The effect of δI_A is to introduce magnetostrictive expansion of A, so that if the wire does not curve there results a compressive stress in A and a tensile stress in B. These new stresses now produce further increments of decrease of I.

[15] R. Forrer, reference 3; M. Kersten, reference 7.

[16] The curves for compressed nickel are not given in Figs. 3, 4, and 5. However, the differences between stretched and compressed nickel will be similar to the differences between stretched and unstretched nickel. The magnitude of the differences will, of course, be greater in the former case.

From the foregoing it is clear that conditions are such as to produce instability. The decrease of magnetization of the compressed segment, produced by a small increase of the demagnetizing, field, introduces strains which tend to increase the magnetization change which produced them. Discontinuities of magnetization of the composite wire will thus appear for demagnetizing fields beyond the point P.

The large changes of magnetization produced by the above means would end when the strains produced by magnetostriction tend to inhibit the magnetization changes which produce them. It appears that this condition is met with as soon as all the residual magnetism is removed and I begins increasing in the direction of the field.[17] In other words, a discontinuity of I, initiated above the H axis on the descending branch of the hysteresis loop, would not be expected to extend below the H axis.

It is a fact that the large Forrer discontinuities may be initiated in the demagnetization section of the hysteresis loop and that they frequently do not cross the H axis. On the other hand, there are instances where almost the entire left side of the hysteresis loop consists of a single discontinuity. It would appear, therefore, that conditions of instability must be present in many cases, even after all residual magnetization has disappeared and the I vector is increasing in the direction of the field.

Possibly it is not correct to assume, as we have done above, that nickel has its maximum length at the point where I passes through zero and begins increasing in the direction of the field. This assumption is not in agreement with the experimental work of Schulze, whose nickel begins to contract as soon as I is reduced below about 150. (It expands while I is being reduced from saturation to 150.) The curves of McKeehan and Cioffi, however, appear to indicate that $I=0$ when the slope of the dL/L curve is zero, in agreement with Fig. 6. Also from the standpoint of theories involving orientation of atomic magnets this assumption is the natural one to make. Schulze's curves, therefore, appear to require further experimental corroboration before they can be accepted.

The theory of the large discontinuities of magnetization given above may be applied to the much smaller Barkhausen discontinuities which usually require an amplifying device for their detection. Suppose that in a ferromagnetic substance there are small regions in a condition of strain similar to that assumed for the composite wire above. Then each of these small regions will contribute its own discontinuity to the magnetization curve. In this way the ordinary Barkhausen effect would be produced. The existence of these highly localized strains is not improbable. Recent experimental and theoretical work[18] has demonstrated that a ferromagnetic crystal is made up of small

[17] We assume that the contraction begins as soon as I begins increasing. In this case an increment, ΔH, causing an increment, ΔI_A, in the compressed segment, produces magnetostrictive strains which decrease the degree of compression of the compressed segment. A decrease of compression would produce a decrease of I. The strains produced by magnetostriction thus tend to inhibit the magnetization changes which produce the strains.

[18] F. Zwicky, Phys. Rev. [2] **38**, 1772 (1931); F. Bitter, Phys. Rev. [2] **37**, 91 (1931); **38**, 1903 (1931).

blocks which are more or less independent of each other in their magnetic behavior. These blocks will be the seat of local strains because of the differences in their magnetic condition. Webster's theory,[19] which accounts for magnetostriction in unsaturated states, assumes that small regions are magnetized to saturation in various directions, the crystal as a whole not necessarily showing any resultant magnetization. The small regions are supposed to possess natural directions of easy magnetization.

A system of this kind would inevitably lead to a complicated pattern of internal strains associated with the blocks. An increasing magnetic field merely rotates the magnetization vector of each element without changing its magnitude. However, since each block expands transversely to its magnetization vector and contracts parallel thereto, it is evident that rotation of the separate vectors, either into or out of the condition of random orientation would set up strains of an elastic character between separate blocks. Whenever these strains produce magnetic instability a Barkhausen jump of magnetization occurs.

Experimental evidence has been obtained by Preisach[20] that the Barkhausen effect is fundamentally of the same nature as the large Forrer discontinuity. Stretching a wire of Fe-Ni alloy caused the small discontinuities to merge into a single large one; we may therefore suppose them to arise from the same underlying cause. Although the large discontinuities sometimes obtained in alloys may not be as simply explained as in the case of pure nickel, it appears evident that no theory of the effect can be satisfactory unless it considers strains as of fundamental importance in the whole phenomenon.

[19] W. L. Webster, Proc. Phys. Soc. **42**, 431 (1930).
[20] F. Preisach, Ann. d. Physik [5] **3**, 737 (1929).

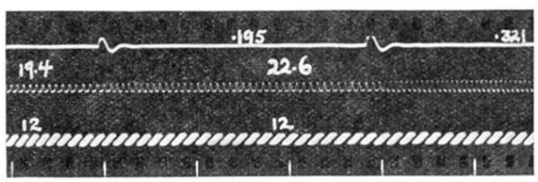


Fig. 2. Oscillograph record. Top trace = solenoid current; middle trace = heterodyne note; bottom trace = time scale.