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Measurements of Magnetic Viscosity in Iron

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Magnetic viscosity—the change of induction occurring after the magnetizing field has ceased to vary—has been measured in a bar of commercial iron, with a measuring circuit designed to eliminate spurious effects arising from sparking at switches. Magnetic viscosity is found to depend on previous magnetic states, in agreement with observations of Mitkevitch and contrary to Preisach's results. It appears, therefore, as if reversible domains could retain their lagging propensity while the magnetic force is varying over a considerable range. The viscous effect is found to depend on the magnitude of the previous change of induction if the latter is small, but is independent of this change if it is greater than 60 gauss. In small, subsidiary hysteresis loops, such as are used in determining reversible permeability, it is found that the Barkhausen effect is not present although there is hysteresis and magnetic viscosity. It is therefore concluded that the movement of the boundaries of saturated domains in the material is subject to time-lag.

When a ferromagnetic material is subjected to a magnetizing field and this field is suddenly changed, the magnetic induction in the material will, in general, continue to change for an appreciable time after the magnetizing field has ceased to vary. Eddy currents in the specimen are responsible for part of this time-lag in magnetization. By a method given by Rayleigh[1] it is possible to calculate the magnitude of this part of the phenomenon. In addition to the effect arising from eddy currents there is another time-lag which may persist long after the eddy currents have died away. The cause of this additional time-lag of induction, usually called magnetic viscosity, is not clearly understood at present. In the experiments described below measurements of magnetic viscosity in commercial iron wire have been made, and certain factors which modify this viscosity have been investigated.

Experimental Technique

Figure 1 gives a diagram of the apparatus used. A pendulum closes switch K_1, and shortly afterwards, K_2. When K_1 is closed the current through the solenoid C is short circuited and the field in C falls practically to zero. The induction in the iron specimen S continues to change after K_1 closes, and with the closing of K_2 the galvanometer G begins to deflect as a result of the induced e.m.f. in the pick-up coil P. This deflection is quickly brought back to zero by closing the switch K_3, thus adding through the mutual inductance M enough flux in the galvanometer circuit to balance the flux removed from P. As the magnetic induction of S continues to decrease the rheostat R_3 is varied by hand so as to keep the galvanometer deflection zero. From the final reading of the ammeter A_2 (after no more induction decrease can be observed), the number of turns in P, the mutual inductance M, and the cross-sectional area of S, it is possible to calculate the change of induction which occurred in S after the closing of the switch K_2.

This method is superior to the ballistic method because the inductive changes may be followed over a long period of time. Another advantage of the circuit shown in Fig. 1 is that it eliminates uncertainties connected with the spark produced when a switch is opened in an inductive circuit. An extended series of measurements was made with a circuit in which the solenoid current was reduced to zero by opening a switch in series with the battery. It was found that when proper values of resistance and capacity were used as shunt across the solenoid so as to produce

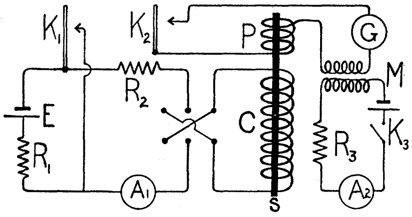

Fig. 1. Circuit diagram.

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[1] Lord Rayleigh, Rep. Brit. Assoc. 52, 446 (1882).

theoretically a nonoscillatory decay of current in the solenoid, nevertheless a high frequency oscillation of short duration occurred at the instant of break. This oscillation was detected with a cathode-ray oscillograph connected across a noninductive resistance in series with the solenoid. Under certain conditions no magnetic viscosity whatever could be observed, probably because of the spark oscillations superposed on the unidirectional decay current. Under other conditions of resistance and capacity these superposed spark oscillations did not appear to affect the viscosity. Pending a more complete investigation of this phenomenon it was decided to eliminate uncertainties by the use of the short-circuiting device of Fig. 1. There is a very definite probability that some of the conflicting results of previous experimenters may be due to the unsuspected presence of spark oscillations in their circuits.

Further details of the circuit are as follows: The galvanometer was of the high sensitivity type, of period 19 seconds, used with a scale distance of 470 cm. It was necessary to insulate the circuits with considerable care in order to avoid spurious effects. The battery E was a 6 volt storage battery. The solenoid C, wound on a micarta tube, was 30.6 cm long, contained 7000 turns, and had a resistance of 42.5 ohms. Its mean diameter was 9.26 cm. The coil P had 10,000 turns and was supported in the center of the solenoid. The specimen S was centered with respect to C and P. It was a wire of commercial iron, 0.30 cm in diameter and 15.1 cm long. It was annealed by slow cooling from a bright red heat. Figure 2 gives the descending branch of the hysteresis loop of this specimen, without correction for the factor of demagnetization.

In order for the eddy currents to have time to die away in a specimen of this diameter it is necessary to have a fairly large time interval between the closing of switches K_1 and K_2. In most of the work the switches were set so that this time interval, by calculation, was 0.61 seconds. During this time the current in the solenoid must fall to a negligible value and the eddy currents in the specimen must die away. If R_2 in Fig. 1 is taken to be 100 ohms, the value usually used, a simple calculation shows that 0.13 second after the closing of K_1 the current in C is reduced by the factor 1.1×10^{-6}. The maximum current used in the experiments was 0.125 ampere. Thus after 0.13 second the current has fallen to a value 1.4×10^{-7} ampere. Tests showed that with the specimen in the solenoid the induction changes caused by a current of 6×10^{-7} ampere produced no detectable effect on the galvanometer. We may therefore assume the solenoid current to be zero 0.13 second after the closing of K_1. The eddy currents—and therefore the magnetic induction—in the specimen will require some time to die away after the solenoid current has become zero. Rayleigh's formula for the decay of eddy currents may be put in the form $\log b = -1.44t/(A\sigma\mu)$, where b is the fraction of the total induction change which occurs after a time t, and t is the time after the magnetic field is removed; σ and A are the conductivity and cross-sectional area, respectively, of the specimen. The value of the permeability μ is set equal to dB/dH and can be obtained from the B–H curve of Fig. 2 after the appropriate factor of demagnetization has been applied. By using the least favorable value of dB/dH and taking $t=0.48$ second, which is the time remaining after the solenoid current becomes effectively zero before K_2 is closed, b is calculated to be 2.6×10^{-6}. The maximum value of the total induction change in the experiments where viscosity was measured was 6400. Thus we obtain for the induction change ($\delta B=6400b$) which occurs after K_2 is closed, and which is caused by eddy currents, the value 0.017. The smallest induction

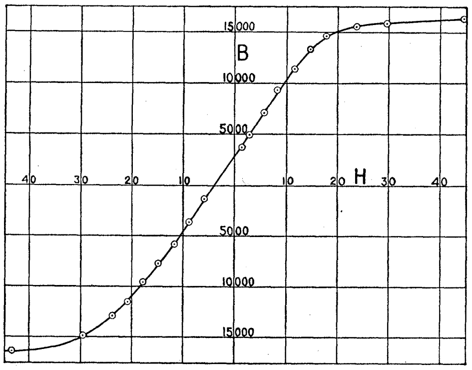

FIG. 2. Descending branch of the hysteresis loop of a commercial iron wire which had been annealed by slow cooling from red heat. No correction has been made for demagnetization.

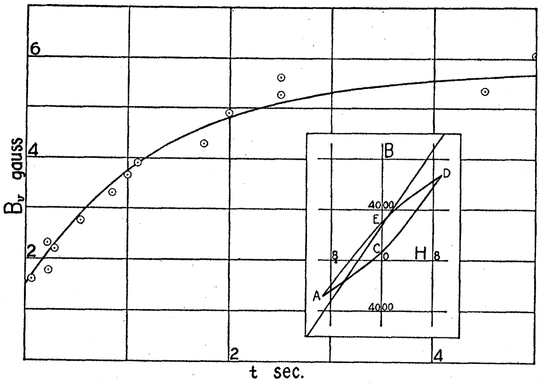

FIG. 3. The magnetic viscosity of iron as a function of the time it was kept at the point D of the hysteresis loop.

change which could be detected with certainty by the apparatus was about 0.2 gauss. Thus any effect arising from eddy currents is too small to be detected in any of the present experiments.

INFLUENCE OF PREVIOUS MAGNETIC STATES

The small hysteresis loop shown in Fig. 3 was traversed several times so as to stabilize the loop. The viscosity at E following the drop from D was then measured and found to depend on the length of time the iron was kept at point D. The experimental points on the large curve of Fig. 3 were obtained as follows. The iron was left at state A of the small loop for about one minute—a sufficient time for all appreciable viscous effects to disappear—then by a reversing switch carried to state D. After a time t the pendulum was allowed to close key K_1, and 0.61 second later, K_2. Thus the iron was carried to state E and the viscous effect, B_v, measured. In order to measure t a noninductive resistance of 40 ohms was connected in series with the solenoid and potential leads from the ends of this resistance were led to the filament and grid, respectively, of a triode amplifying tube. When the reversing switch was thrown the potential change across the 40 ohms caused a change of plate current and thus actuated, through a sensitive relay, the stylus of a revolving drum chronograph. When the key K_1 closed the stylus was again actuated. In this way a sufficiently accurate determination of t could be made.

Figure 3 shows that the magnetic viscosity, B_v, at E is diminished when t is reduced below about 3.5 seconds. For larger values of t it appears that B_v is constant as t changes. In interpreting the curve it is to be noted that when t is less than about 0.3 second the iron at D may still be the seat of eddy currents of appreciable magnitude at the instant the key K_1 is closed. However, it is quite evident that after all eddy currents have died away there is still a magnetic readjustment going on at D which must be completed if the full value of the viscosity at E is to be obtained. When the iron is carried to D we may say that the magnetic viscosity at that point consists in the reversal of lagging magnetic domains, so that the induction at D continues to increase for some time after point D is reached by the magnetic field. If all of these lagging domains are not allowed to reverse before the field is reduced to the value at E we do not find so big a viscous effect at E. The decrease of viscosity at E is due to the fact that certain members of a group of viscous domains have not had time to reverse at D, hence these members are oriented in the right direction at E and do not need to reverse under the influence of the demagnetizing field.

Let N_D and N_E be the numbers of domains which show magnetic viscosity in reversing at the respective points D and E. Assume (1) that members of the group N_D which do not have time to reverse their magnetism at D are detracted from the viscous group N_E at E; (2) that the number of unreversed viscous domains at D varies exponentially with the time t after the field becomes constant. That is, let $N=N_De^{-mt}$, where N is the number of domains still unreversed t seconds after the field has ceased to vary, and m is a constant.

The measured magnetic viscosity at E is then given by $B_v=k(N_E-N)=k(N_E-N_De^{-mt})=k_1-k_2e^{-mt}$, where k, k_1, and k_2 are constants. The curve of Fig. 3 is drawn with $k_1=5.75$, $k_2=4.25$, and $m=0.75$ in the above equation. The experimental points fit the curve as well as could be expected.

A consequence of the above equation for B_v is that when point D is chosen far out on the saturated part of the magnetization curve the value of B_v should be independent of t; for in this case the viscosity at D is found experimentally to be very small, so that N_D may be set equal to zero and thus $B_v=k_1$. The constant k_1 in this case, however, may be different from the k_1 for other positions of D, because, in general, N_E depends on the previous magnetic history of the specimen. Experimental tests showed that when point D is taken to a field of 34 gauss the value of B_v at C is about the same, whether t is 0.3 second or one minute.

In case N_D is larger than N_E the value of B_v would be negative for small values of t. The specimen of iron used in this experiment did not give negative values of B_v for the part of the hysteresis loop examined. Previous experiments disagree to some extent in this matter. Mitkevitch[2] and Richter[3] were able to observe the negative effect predicted by the above equation. Preisach[4] not only failed to report the negative effect but also he states that the time during which a specimen is subjected to a field has no effect on the viscosity appearing when the field is cut off. Preisach states that the "superposition principle" is not applicable to magnetic viscosity. The conflict between the results of Preisach and those of Mitkevitch, Richter, and the writer could very well be due to the presence of spark oscillations in the solenoid of Preisach. He does not give a diagram of his circuit nor does he mention any precautions taken to stop oscillations.

Relation Between the Magnitude of an Induction Change and the Ensuing Magnetic Viscosity

The procedure in this experiment was as follows. From a saturating field of 35 gauss the field was decreased to a definite small value, H', and kept constant at that value for one minute. Then the pendulum was allowed to operate the switches K_1 and K_2, thus removing the field H', producing the induction decrease ΔB, and allowing the resulting magnetic viscosity B_v to be measured. Curve I of Fig. 4, obtained in this way, shows that B_v is constant for large values of ΔB but diminishes rapidly when ΔB is decreased below about 60 gauss.

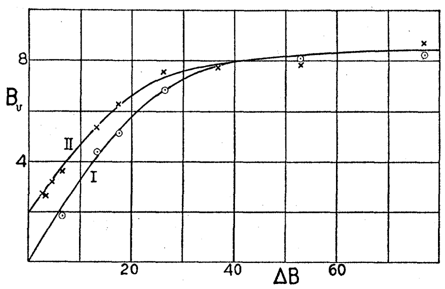

FIG. 4. Magnetic viscosity of iron as a function of the induction decrease ΔB.

If the time of holding H' constant is diminished from one minute to 5 seconds curve II is obtained. Curves I and II coincide for large values of ΔB but below 50 gauss curve II is the higher.

These curves show that the number of viscous domains which reverse after the induction jump ΔB has occurred is practically independent of the magnitude of ΔB when the latter is large, but as ΔB becomes small this number decreases. Curve II is higher than I because for the former curve some of the viscous domains which had no time to reverse during the pause at H' remain unreversed during the change ΔB and thus contribute to the viscosity after ΔB has occurred. The curve II does not pass through the origin because when the saturating field of 35 gauss is brought to zero for 5 seconds and no further change made, i.e., $\Delta B = 0$, then even after 5 seconds there are still numerous domains which have not yet had time to reverse. These domains give the viscosity measured when K_2 is closed at the end of the 5 seconds.

Relation Between Magnetic Viscosity and Barkhausen Discontinuities of Magnetization

In the previous experiments if the galvanometer is replaced by an amplifier and telephone receivers it is possible to detect Barkhausen discontinuities which persist and can be heard in decreasing numbers for some time after the magnetic field has ceased to vary. In line with this observation, therefore, it is usually considered that the entire phenomenon of magnetic viscosity is due to the existence of delayed Barkhausen reversals of magnetization. The cause of this delay in the reversal of Barkhausen domains has been attributed[5] to persisting eddy currents and to the resulting microscopic strains

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[2] A. Mitkevitch, J. de phys. **7**, 133 (1936).

[3] G. Richter, Ann. d. Physik **29**, 605 (1937).

[4] F. Preisach, Zeits. f. Physik **94**, 277 (1935).

[5] H. Kuhlewein, Physik. Zeits. **32**, 860 (1931); C. W. Heaps, Phys. Rev. **49**, 409 (1936).

set up by the local inequalities of temperature. The experiments described below indicate that magnetic viscosity is not to be explained entirely in terms of these delayed Barkhausen reversals.

A small subsidiary hysteresis loop similar to that shown in the inset of Fig. 3 was examined, with an amplifier and telephone receivers, for a lagging Barkhausen effect at the points A, C, D, and E. At these same points the magnetic viscosity was also measured with the galvanometer as described above. It was found for a loop of large area that Barkhausen jumps and magnetic viscosity were both present at all the specified points. When the loop was made smaller and stabilized by repeated traversing of the cycle the Barkhausen jumps disappeared at certain of the points.

For example, when the limits of variation of B and H were, respectively, 390 and 1.6 gauss no Barkhausen effect could be detected at any of the points. The magnetic viscosity, however, amounted to 1.0 gauss at each point. This figure represents, as before, the total induction change occurring 0.61 second after the solenoid current is switched on or off. For points A and D this time is only approximate, as here the key K_1 could not be used and it was necessary to close the reversing switch, and subsequently K_2, by hand. In observing the Barkhausen effect the amplifier system which had been substituted for G was kept connected at all times, i.e., K_2 was kept closed. Thus when the reversing switch was operated there was always a loud, sharp noise caused by the big inductive jump. This noise was followed, in case of lagging Barkhausen jumps, by a crackling, or popping noise which gradually died away as the individual impulses became less frequent.

For the loop of limits specified above this lagging Barkhausen effect was at first large at point A. After about five circuits of the loop it vanished at this point. The other points of the loop showed no lag at any time. The magnetic viscosity as measured with the galvanometer showed a similar initial large effect at A—approximately 9 gauss—which diminished to the constant value 1.0 gauss after about eight circuits of the loop.

It seems improbable that this viscous effect of 1.0 gauss is due to Barkhausen jumps too small to be heard in the telephone receivers. As the Barkhausen effect diminishes with successive trips around the loop it is not the intensity of the individual impulses which seems to weaken, it is their number. It appears, therefore, as if the members of a definite group of lagging, reversible domains were gradually removed from this lagging group by repeated trips around the loop. If the magnetic viscosity which remains after several cycles is due to discontinuities of magnetization these discontinuities must be of a different order of magnitude from those ordinarily observed because none whatever could be detected even when four stages of amplification were used.

Small loops of the kind here described are used in determining reversible susceptibility. The area of these loops may be made very small by decreasing the amplitude of the field variation but the statement which is sometimes made[6] that these small cyclic processes involve no dissipation of energy appears to be incorrect according to the best experimental evidence.[7] It is only in the limit, as the amplitude of the field variation approaches zero, that the area becomes zero. For the loop as used above the width along the B axis was about 45 gauss. Accordingly the disappearance of lagging Barkhausen jumps is not to be attributed to the disappearance of hysteresis.

The question arises as to whether the Barkhausen discontinuities merely fail to lag behind the field or disappear for all points around the loop. An experimental test of this question was made as follows. The field was caused to vary slowly and continuously around the loop and simultaneously a check was made, with the use of the telephone receivers, to see whether Barkhausen discontinuities occurred. The slow continuous field variation was obtained by passing the plate current of a radio tube, type 89, through the solenoid. When the heater current of the tube was switched on or off the plate current rose or fell smoothly and slowly. After several cycles had stabilized the loop no Barkhausen jumps could be detected at any point. Accordingly we conclude that in these small

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[6] F. Bitter, *Introduction to Ferromagnetism* (McGraw-Hill Book Co., 1937), p. 182.

[7] E. Spuhrmann, Zeits. f. Physik **39**, 332 (1926); K. Uller, Zeits. f. Physik **38**, 72 (1926); G. J. Sizoo, Ann. d. Physik **3**, 270 (1929).

subsidiary loops there is hysteresis and magnetic viscosity without any Barkhausen effect.

According to the domain theory of ferromagnetism a material may change its intensity of magnetization by three different processes: (1) reversal of the saturated magnetization of small domains, (2) reorientation of the magnetization of the domains, (3) increase of size of one domain at the expense of another. The first process is supposed to produce the sudden inductive jumps associated with the Barkhausen effect. The last two processes may take place slowly and continuously, so would not be detected by the use of telephone receivers. It appears, therefore, in view of the experiments just described, that the phenomenon of magnetic viscosity is involved in one or both of the two last named processes, as well as in the first.

It is usually considered that process (2) occurs in strong fields, process (3) in weak fields.[8] For the loop used in the present experiment there is always a demagnetizing field present; however, it seems reasonable to suppose that process (3) is largely responsible for the induction changes of these small loops.

In this case the conclusion to be drawn is that when the boundaries of domains move under the influence of applied fields a certain time is required for equilibrium to be attained after the magnetic field ceases to change. These moving boundaries would be the seat of eddy currents and magnetostrictive strains, so that magnetic viscosity would make its appearance in process (3) as a result of the time required for the disappearance of microscopic temperature gradients and the readjustment of the local strains.

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[8] F. Bloch, Zeits. f. Physik **74**, 333 (1932); R. Becker, Physik. Zeits. **33**, 905 (1932).

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The Variation of the Elastic Constants of Crystalline Sodium with Temperature Between 80°K and 210°K*

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Methods are described for growing single crystals of sodium in the form of rods 4.7 mm in diameter and 10 cm long, for handling the crystals in an atmosphere of helium, and for measuring the principal elastic moduli at low temperatures. Values of the adiabatic and isothermal moduli and constants are tabulated at ten degree intervals between 80°K and 210°K. The value of the Debye characteristic temperature, calculated from the values of the elastic constants at 80°K, is 164°K.

Experimental Method for Measuring the Elastic Constants

A COMPLETE description of the dynamical method employed in this research has appeared in previous issues of this journal.[1] Accordingly, it will suffice here briefly to review its essential features, and their adaptation to the present experimental problem. The specimen is in the form of a right circular cylinder 4.7 mm in diameter and a few centimeters long. The required data are deduced from the observed behavior of a separately excited composite piezoelectric oscillator constructed by cementing to one end of the specimen a suitably cut cylinder of crystalline quartz of identical cross-section. Silver electrodes are chemically deposited in proper position on the quartz, and the oscillator is suspended vertically by delicate supports attached at the middle of the quartz cylinder. One or more harmonic frequencies of free longitudinal or torsional vibration of this system are measured by observing the variation of the electrical impedance of the composite oscillator with the frequency of the applied voltage, and

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[1] Balamuth, Phys. Rev. **45**, 715 (1934); Rose, Phys. Rev. **49**, 50 (1936); Durand, Phys. Rev. **50**, 449 (1936).