The Magnetostriction, Young's Modulus and Damping of 68 Permalloy as Dependent on Magnetization and Heat Treatment

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This paper describes measurements of the changes in certain physical properties of 68 Permalloy that result from different thermal and mechanical treatments and considers them in relation to the domain theory. The magnetostriction varied with heat treatment from 2.5×10^{-6} to 22×10^{-6}. The change in Young's modulus with magnetization to saturation varied from 0.09 to 10.5 percent. The damping of mechanical vibrations was also measured as dependent on magnetization and heat treatment. Young's modulus and the damping constant were determined by measuring the natural frequency of vibration and the width of the resonance curve of a hollow rectangle magnetized parallel to its sides so that the magnetic circuit was complete without air gaps or end effects.

THE magnetostriction, Young's modulus and vibrational energy loss have been determined as a function of the magnetization for specimens of 68 Permalloy each of which had been given one of five different mechanical or heat treatments.

The alloy studied was chosen because it has a very small magnetic anisotropy constant[1] and is especially sensitive to heat treatment. The results were expected to help in elucidating the domain structure of ferromagnetic materials. On the basis of a theory[2] of the heat treatment in magnetic fields, proposed previously, it was predicted that the magnetostriction at saturation after heat treatment in a longitudinal field would be zero and after treatment in a transverse field would be $\frac{3}{2}$ times the value obtained after the usual treatments. As pointed out to us by Mr. J. S. Marsh, the change in Young's modulus caused by magnetizing to saturation should, according to this theory, be very small after heat treating in a longitudinal field, as compared to the changes in the material heat treated in other ways. In a qualitative way the measurements of magnetostriction conform well to the predictions—the magnetostriction of the specimen heat treated in a longitudinal field is only a few percent of the normal value for intensities of magnetization below 90 percent of saturation, and at saturation rises to approximately 12 percent of the normal value. A similar statement may be made for the variations of Young's modulus with magnetization. For each property the theory is quantitatively inadequate.

The magnetostriction was determined by measuring the change in length of the rectangular specimen, using a mirror attached to a roller pressed against the specimen. An increase in amplification is attained by inclining the axis of the specimen to the direction in which the roller is constrained to move. The change in Young's modulus with magnetization was determined by measuring the change in frequency of mechanical vibration in the fundamental longitudinal mode, and the logarithmic decrement by measuring the width of the resonance curve. The methods are described below in more detail.

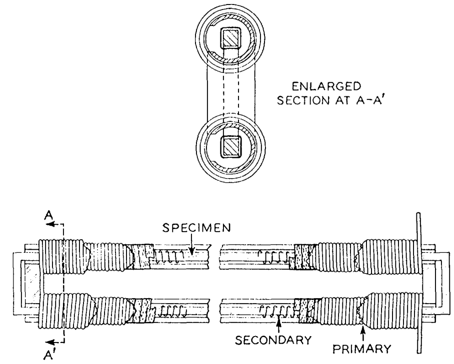

FIG. 1. Specimen, with windings, used for measuring magnetostriction and magnetization for various applied field strengths. The over-all length of the specimen is 30.4 cm, its width 2.54 cm, and its cross section 0.318 cm square.

[1] E. M. Grabbe and L. W. McKeehan, Phys. Rev. **55**, 1142 (1939); E. M. Grabbe, Phys. Rev. **57**, 728 (1940); H. J. Williams and R. M. Bozorth, Phys. Rev. **55**, 673 (1939).

[2] R. M. Bozorth and J. F. Dillinger, Physics **6**, 285 (1935); see also reference 11, p. 217.

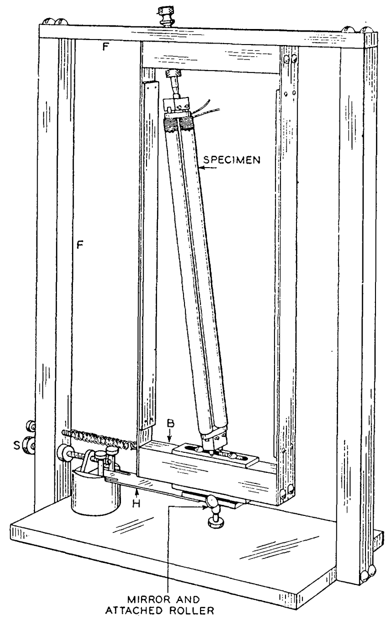

FIG. 2. Apparatus for measuring magnetostriction. *F* is a solid framework, *B* (supported by flexible strips) the bar upon which the specimen rests, *H* a flexible strip held against roller by spring, *S* an adjusting screw. Expansion of specimen moves *B* to right, turns roller and mirror and deflects beam.

SPECIMENS AND TREATMENT

In previous measurements of Young's modulus as affected by magnetization, closed magnetic circuits have not been used and it has been necessary to correct for the demagnetizing influence of the ends of the specimen and to tolerate non-uniformity of magnetization even in the strongest fields. This difficulty has been overcome in the present investigation by cutting the specimen in the form of a hollow rectangle to form a closed magnetic circuit, as shown in Fig. 1. Magnetizing windings were wound around the long sides of the specimens but were supported by tubes to prevent the winding from touching the specimen. A negligible error is attributable to the four corners where the flux executes a rather sharp bend.

The alloy was made from iron and nickel of high commercial purity, melted in a high frequency induction furnace and cast as a $\frac{3}{4}$-inch plate. This was rolled cold to $\frac{1}{8}$-inch and the specimens cut with a length of 12 inches, a width of 1 inch and cross section of $\frac{1}{8}$ inch square. In addition to a nickel content of 68 percent, 0.3 percent manganese was added to make the alloy form easily. The mechanical and heat treatments were as follows: (a) Hard rolled, 83 percent reduction in thickness. Unannealed. (b) Annealed at 1000°C in hydrogen for one hour, cooled slowly (about 5°C/minute through 500°C). (c) Treatment (b), then heated to 600°C and cooled rapidly in air (about 1000°C/minute through 500°C). (d) Treatment (b) then heated to 600°C in hydrogen and subjected to a magnetic field of 10 oersteds which was maintained during slow cooling. The applied field was *longitudinal*, that is, its direction was parallel to the direction of the field applied later for measurement. (e) The same as (d) except that the field was *transverse*. This was applied by passing a current of 30 amperes through the specimen from end to end. The field strength was thus about 15 oersteds at the surface and zero at the middle of the cross section.

METHODS

Magnetostriction

The change in length was measured with the aid of the well-known combination of a roller and mirror. As shown in Fig. 2, the specimen is held about 8° from the vertical with its upper

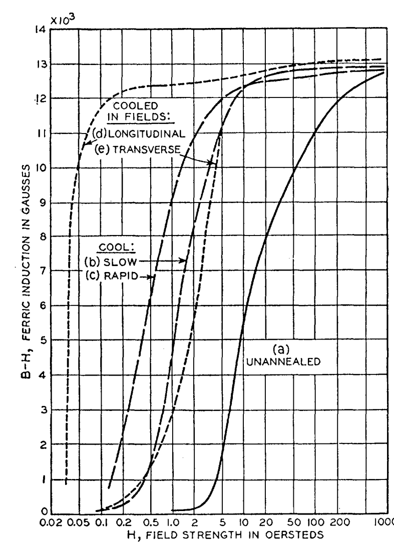

FIG. 3. Magnetization curves of specimens treated in ways indicated. Initial permeabilities are 54 for (a), 5700 for (c) and 3300 for (e); measurements were not made for the other specimens but data on similar materials indicate that they are 3000 to 3500.

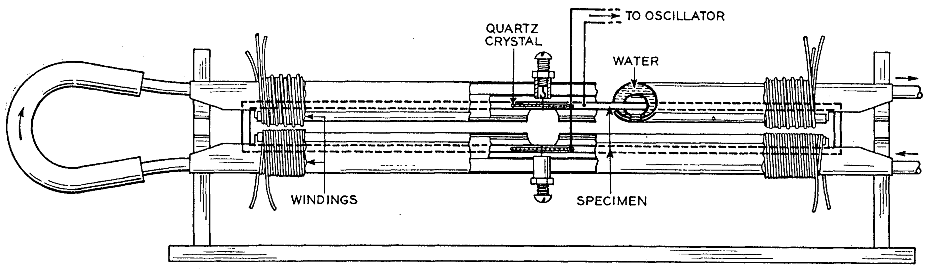

FIG. 4. Apparatus for measuring Young's modulus. Specimen is held by threads at middle and vibrated by quartz crystals. Magnetization is controlled by current in winding. Constant temperature is maintained by water cooling.

point fixed with respect to a heavy frame F. Suspended from this frame are two vertical bars with flexible strips at each end, and these support a heavy horizontal bar B upon which the lower end of the specimen rests. The roller, 1 mm in diameter, is held between two plates, one of which is fastened to the bar B, and the other of which is fastened to the frame F, by a horizontal flexible strip H. The plates were milled lengthwise and lapped, and a strip down the middle was cut to a greater depth so that the roller made contact only along the edges of the plates. The roller and plates were of hardened steel and were held in contact by a spring not shown. Another spring exerted a slight pull on the bar B, so that the specimen would remain in

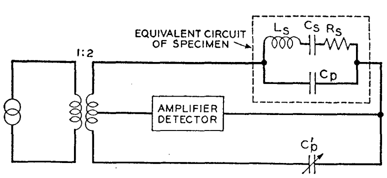

FIG. 5. Electrical measuring circuit for vibrating specimen and measuring its relative amplitude. The oscillator is at the left. C_p is the capacity of the quartz electrodes; C_p' the capacity for balancing C_p; L_s, R_s, and C_s the effective inductance, resistance and capacity of the specimen.

contact at the proper points; tests showed that varying the tension made no difference in the results. The contacts at the two ends of the specimen were steel cones fitting into conical holes having a considerably larger angle. The magnetizing coil was wound on a frame fitting loosely around the specimen so that the expansion of the latter was not restricted.

Because of the fact that the length of the specimen made a large angle with the direction of the displacement of the bar, a change in the length of the specimen caused a seven times larger displacement of the bar B than it would if the specimen were parallel to the displacement. However, the fact that the bar was constrained to move in a definite path by its supports did not permit the magnification by this factor of any errors due to irregularities in the dimension of the roller. A beam of light was reflected from the mirror onto a scale 2 meters distant. A scale reading of 1 mm corresponded to a fractional change in length of 1.47×10^{-7}. The mirror could be rotated into the desired position by means of the screw S. Readings were obtained by first demagnetizing the specimen and then applying a certain magnetizing force. Measurements of magnetization were made simultaneously by means of a fluxmeter. Because of the large thermal lag it was possible to obtain the deflection due to magnetostriction before the heat generated in the windings caused the specimen to expand on account of its change in temperature. Magnetization curves of all specimens are shown in Fig. 3.

Young's modulus

The change in Young's modulus with magnetization was determined from measurements of the natural period of longitudinal vibration before and after magnetization. As shown in Fig. 4, the specimen was held by two stretched threads, one above and one below the specimen, and was excited in the longitudinal mode by impressing an alternating voltage on four quartz crystal plates, each $25\times3\times0.5$ mm, placed on opposite sides of the two long arms of the specimen, at the middle. The quartz crystals were cut in the usual way in the $(11\bar{2}0)$ plane

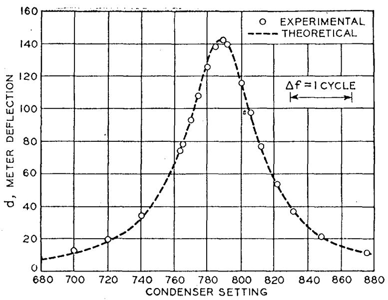

FIG. 6. A typical resonance curve. The unit of the condenser setting is 0.60×10^{-6} microfarad. The calculated curve is adjusted for maximum height and for width at half-maximum. The ordinate (read as microamperes) is proportional to the square of the amplitude of motion of the specimen. A change in frequency of one cycle corresponds to a change in condenser setting of 37 units.

with the mechanical axis [1$\bar{1}$00] parallel to the long dimension and were covered on their largest surfaces by aluminum deposited from the vapor. They were cemented to the specimen with a thin layer of sealing wax. As shown in Fig. 5, leads from the aluminum-covered surfaces connected the crystals in parallel to the rest of the circuit. This method of excitation and measurement were suggested to us by Mr. R. F. Wick of these laboratories. Magnetizing windings were wound around water-cooled supports which surrounded the specimen and were maintained at a constant temperature.

The oscillator, able to cover the range from 20 to 100,000 cycles per second, was connected to a transformer with primary and secondary impedances in the ratio 1 : 2. A tap in the middle of the secondary was connected to an amplifier having a gain of 90 decibels, the output of the amplifier to a rectifier and this to a microammeter, the readings of which were proportional to the mean square voltage at the amplifier input. The electrical effect of the quartz plates and specimen are simulated by capacity, inductance and resistance as shown. The capacity was balanced by adjusting the condenser in the other arm of the bridge when the frequency was far from the resonant frequency and the output of the amplifier-detector was measured as the frequency was changed in small steps in a range including the resonance.

Changes in frequency were determined accurately in terms of the setting of a carefully calibrated variable air condenser of total capacity 0.0015 microfarad, placed in parallel with the main condenser of the oscillator. The smallest division on this condenser corresponded to a change in frequency of one part in 3,000,000 at 7000 cycles per second. The over-all error in measuring fractional changes in frequency is estimated as less than one part in 1000.

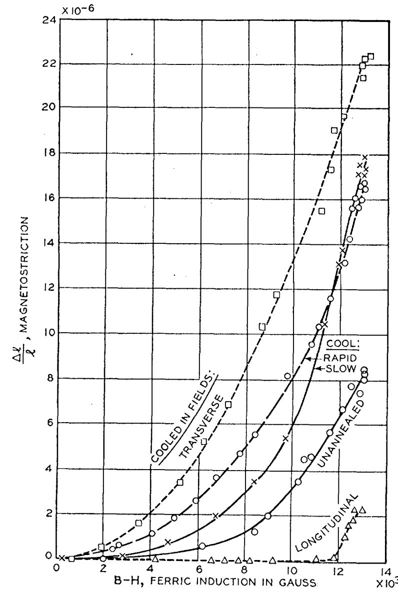

FIG. 7. Magnetostriction as a function of magnetization for specimens treated as indicated.

The frequency of resonance f permits calculation of Young's modulus E by means of the relation

$$f=(n/2l)(E/\rho)^{\frac{1}{2}} \tag{1}$$

appropriate for longitudinal modes with a node at the middle. Here l is the effective length of the specimen, ρ is the density and n an odd integer. Because of the added weight on the end of the specimen the effective length l was not the measured length l_0. The ratio of these lengths was determined by comparing the resonant frequency of the hollow rectangular specimen with that of a single straight square rod cut from one side of the same specimen, and found to be

$$l/l_0=1.048. \tag{2}$$

The frequencies were determined accurately in the manner described by Stansel.[3]

[3] F. R. Stansel, Bell Lab. Record 19, 98 (Nov. 1940).

The effect of the quartz crystals on the stiffness of the composite bar was investigated by driving the unannealed specimen first in the usual way described above, and then, after removing the crystals, by driving magnetically in the manner described by Wegel and Walther[4] using the specimen itself as one of the magnetic elements. The difference in the frequencies obtained by the two methods was less than 0.05 percent, and led to the conclusion that the modulus measured was, in fact, that of the magnetic specimen and that no appreciable error was caused by the presence of the quartz.

Damping

The decrement δ was derived from the width of the resonance curve at half-maximum. The deflection d of the meter at the output of the amplifier, is proportional to the square of the amplitude of vibration of the specimen, and the frequency f of the oscillator is inversely proportional to the square root of the capacity C in its tuning circuit. Thus we have the following relation between δ and Δf, the full width of the d *vs.* f curve at its half-maximum value, $d_0/2$:

$$\delta=\pi(\Delta f/f_0)=(\pi/2)(\Delta C/C_0).$$

Here f_0 and C_0 are the frequency and capacity for resonance, ΔC is the change in capacity between the two points at which d is $d_0/2$, and Δf is the change in frequency corresponding to ΔC. A typical resonance curve is shown in Fig. 6. The points are observed, the curve is that calculated from the relation

$$C-C_0=(C_0/\pi)[(d_0-d)/d]^{\frac{1}{2}}\delta$$

in which δ is adjusted for best agreement.

Measurements of δ were all made with the specimens vibrating with approximately the same amplitude at resonance. This was accomplished by adjusting the output of the oscillator until the value of d at resonance was about 200 microamperes. The amplitude of the bar was measured by Bragg's method[5] when an unusually high voltage was applied to the crystals, and extrapolation to the low power used in the experiments indicated that under these conditions the amplitude was about 10^{-9} cm/cm.

[4] R. L. Wegel and H. Walther, Physics 6, 141 (1935).
[5] W. H. Bragg, J. Sci. Inst. 6, 196 (1929).

Results and Discussion

Magnetostriction

Figure 7 shows the magnetostriction for the various specimens as dependent on the magnetization. The magnetostriction at saturation is greatest for the specimen heat treated in a transverse field and smallest for the one heat treated in a longitudinal field. The magnetostriction for the latter is negligible up to a flux density of approximately 12,000 gauss and then increases to only 2.3×10^{-6}. According to domain theory, when a specimen is heat treated in a longitudinal field the domains tend to lie in the direction of the applied field and after demagnetization they are either parallel or antiparallel to this direction. When a field is applied in the direction of the original field, magnetization consists of 180° reversals which are not accompanied by any change in length. This corresponds closely to the observations.

A large contraction of the specimen heat treated in a longitudinal field was effected by passing a current of several amperes along the axis. This is also in accordance with the domain theory outlined above.

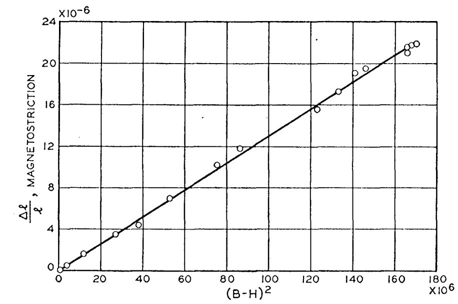

FIG. 8. Magnetostriction of specimen (2) heat treated in a transverse field, plotted against the square of the ferric induction.

In a specimen that has been heat treated in a transverse field the domains lie perpendicular to the direction of the field applied during subsequent measurement. For such an arrangement the expected magnetostriction is thus $\frac{3}{2}$ of that for a random distribution such as may be expected after the usual anneal followed by slow or rapid cooling. This is an effect similar to the unusually large magnetostriction in nickel under

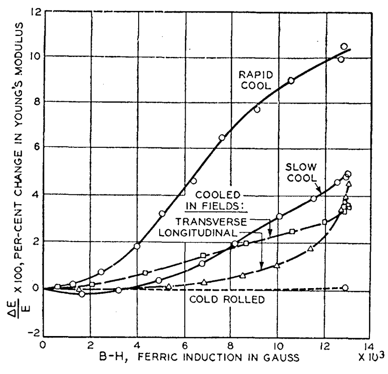

FIG. 9. Percent increase of Young's modulus as dependent on the magnetization for the specimens treated in various ways.

tension, predicted by Becker and Kersten[6] and observed by Kirchner.[7] Lack of perfect agreement with our observations is probably due to nonperfection of alignment, especially of those domains lying near the axis of the bar where the field present during the heat treatment was very small.

The magnetostriction of this specimen is proportional to the square of the magnetization, as shown in Fig. 8. This relation is to be expected if the domains are oriented at right angles to the axis before magnetization and parallel afterwards. If θ is the angle between the axis of the specimen and the direction of magnetization in a domain, the change in magnetization due to the reorientation by the field is proportional to $\cos\theta$ while the change in length is proportional to $\cos^2\theta$; thus the change in length is proportional to the square of the change in magnetization.

The difference in the lengths of a specimen in the demagnetized state and at remanence was found to be only 5 to 10 percent of the change in length that occurred when magnetized originally to saturation. This is commonly observed in magnetic materials generally and is to be expected because the difference in the lengths in the two states (demagnetized and at remanence) is accomplished by 180° reversals of domains which contribute nothing to the length.

The magnetostriction at saturation of the unannealed specimen is considerably less than that of the annealed specimens cooled slowly (b) or rapidly (c). Similar observations on iron have been made by Brown,[8] while Schulze[9] has observed a greater magnetostriction in unannealed than in annealed nickel. These may be due to non-uniform distributions of the orientations of domains resulting, perhaps, from a preponderance of axial strains, but sufficient experiments have not been reported to give a definite conclusion.

Previous to this work, Kaya[10] measured the magnetostriction of various iron-nickel alloys as a function of the magnetization for specimens which had been cooled in a magnetic field, cooled rapidly, cooled slowly, and aged. For the 70 Permalloy, the magnetostriction at saturation was 2.7×10^{-6} for the specimen cooled in the magnetic field, and 11×10^{-6} for the other three specimens. The former value is in good agreement with our result; the latter value is considerably less than our result and also less than that given in Marsh's compilation.[11]

Young's modulus

The variations of Young's modulus with magnetization are given in Fig. 9 for all of the specimens except the hard-worked one, the data for which are shown on a different scale in Fig. 10. The increase in Young's modulus for saturation is slightly over 10 percent for the rapidly cooled specimen and is only 0.088 percent for the cold-rolled specimen. This is in qualitative accord with the theory that this increase in Young's

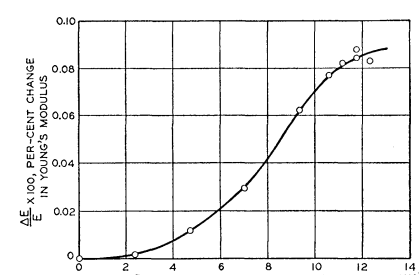

FIG. 10. Percent change of Young's modulus of the unannealed specimen.

[6] R. Becker and M. Kersten, Zeits. f. Physik **64**, 660 (1930).
[7] H. Kirchner, Ann. d. Physik **27**, 49 (1936).
[8] W. F. Brown, Jr., Phys. Rev. **50**, 1165 (1936).
[9] A. Schulze, Ann. d. Physik **11**, 937 (1931).
[10] S. Kaya, J. Faculty Sci., Hokkaido Imp. Univ. **2**, 29 (1938).
[11] J. S. Marsh, *Alloys of Iron and Nickel: I, Special-Purpose Alloys* (McGraw-Hill Book Company, Inc., New York, 1938).

modulus should vary inversely as the internal strain, the latter being measured by the initial permeability. In the case of the rapidly cooled specimen the domains are not "frozen in"—the internal strains are small—and therefore a stress will rotate them easily and Young's modulus for the demagnetized state will be considerably below that for saturation.

The internal strains for the cold-rolled specimen are large and any applied stress has comparatively little effect on rotating the domains. The theory of Kersten[12] may be applied in a quantitative way to this specimen. It gives a relation between the value of $\Delta E/E_0$ attained at saturation, $\Delta E_s/E_0$, and the magnetostriction at saturation, λ_s, the initial permeability, μ_0, and the saturation magnetization, I_s:

$$\Delta E_s/E_0 = (9/20\pi)\lambda_s^2\mu_0 E_0/I_s^2.$$

According to our observations, $\lambda_s = 9\times10^{-6}$, $\mu_0 = 54$, $E_0 = 1.82\times10^{12}$, $4\pi I_s = 13{,}100$ and the calculated value of $\Delta E_s/E_0$ is, therefore, 0.10 percent, a value to be compared with the experimental value, about 0.088 percent. Although in our measurements the magnetization has been carried closer to saturation, and still maintained uniform, than in previous measurements on any hard-worked material, a fact made possible by the closed magnetic path, there is still some uncertainty in $\Delta E_s/E_0$ because heating of the specimen by the high magnetizing current is likely to occur and change the modulus. With this reservation in mind, it may be stated that the agreement between theory and experiment is good.

TABLE I. *Values of Young's modulus of specimens in the demagnetized (E_0) and saturated (E_s) conditions, after various treatments. Units are dyne-cm^{-2}.*

Treatment	$E_0\times10^{-12}$	$E_s\times10^{-12}$	$\Delta E_s/E_0$
(a) Unannealed	1.8145	1.8161	0.00088
(b) Cooled slowly	1.783	1.870	0.049
(c) Cooled rapidly	1.654	1.826	0.104
(d) Cooled in longitudinal field	1.843	1.930	0.047
(e) Cooled in a transverse field	2.105	2.181	0.036

[12] M. Kersten, Zeits. f. Physik **85**, 708 (1933); Zeits. f. Metallkunde **27**, 97 (1935). See also N. Akulov and E. Kondorsky, Zeits. f. Physik **78**, 801 (1932); **85**, 661 (1935); and reference 15, p. 339.

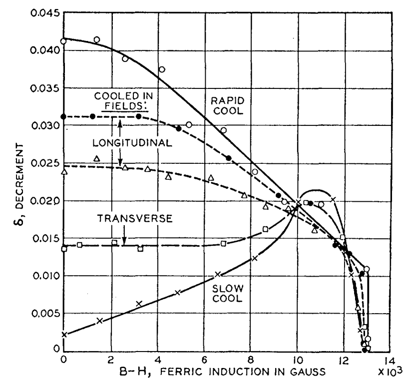

FIG. 11. The decrement as dependent on the magnetization for the heat treated specimens. The decrement of the unannealed specimen at $B=0$ is 0.00053.

The absolute values of Young's modulus for the specimens in the demagnetized state E_0 are given in the second column of Table I. Since the lengths of the specimens were all the same the moduli were proportional to the squares of the natural frequencies of vibration, and the constant of proportionality was determined from Eq. (1). The fractional changes when magnetized to saturation, $\Delta E_s/E_0$, are given in the third column, and the modulus at saturation, $E_s = E_0 + \Delta E_s$, in the last column. It will be noted that E_s does not have the same value after the various treatments, as it would be expected to have according to the domain theory. The reason for this requires investigation. A considerable difference in the values of E_s for the unannealed and the annealed states has also been observed by Cooke[13] who found that in iron the modulus of saturated unannealed iron (1.86×10^{12}) was less even than that of demagnetized annealed iron (1.99×10^{12}). On the other hand a decrease in the modulus on annealing has been observed for nickel.[14]

Our values of E_0 and $\Delta E_s/E_0$ for the slowly cooled alloy are close to those observed by Nakamura[15] for a slowly cooled alloy containing 70 percent nickel. His values were 1.90×10^{12} and 3.6 percent, respectively.

Little can be said regarding the way in which $\Delta E/E_0$ changes with magnetization since our

[13] W. T. Cooke, Phys. Rev. **50**, 1158 (1936).
[14] E. Giebe and E. Blechschmidt, Ann. d. Physik **11**, 905 (1931).
[15] K. Nakamura, Sci. Rep. Tohoku Imp. Univ. **24**, 303 (1935).

measurements of reversible permeability and reversible change of magnetization with tension were not complete enough to deduce from the observed quantities the values of $\Delta E/E_0$ corresponding to zero eddy-current shielding.

Decrement

Figure 11 shows the logarithmic decrement δ as a function of the magnetization for the various specimens. Two different specimens were similarly treated in a longitudinal magnetic field and measured to see how well results could be duplicated. As shown by the two curves the decrements differed by about 20 percent at inductions well below saturation, the general shape of the curve remaining the same. As pointed out by Becker[16] there are three kinds of magnetomechanical losses in energy that occur when magnetic materials are subjected to mechanical vibrations: macro-eddy-current losses, micro-eddy-current losses, and magnetomechanical hysteresis. When the net magnetization over the specimen is zero there will be no macro-eddy-current loss; thus the initial points on our experimental curves refer to the combined losses of micro-eddy-currents and magnetomechanical hysteresis. Some preliminary experiments of ours in which δ was measured as a function of frequency, indicate that at the frequency ($f=7300$) used for the experiments of Fig. 10, about two-thirds of the losses in the slowly cooled specimen (treatment (b)) are due to micro-eddy-currents, and that the domain size calculated from these losses by Becker's method are approximately 10^{-8} cm^3, a size lying just in the middle of the range of sizes determined for a variety of materials by previous measurements[17] of the Barkhausen effect.

The courses of the δ *vs.* $B-H$ curves may be compared with those previously observed for iron and nickel. For annealed iron[13] measured at $f=56{,}000$ the curve rises to a high maximum at about three-fourths of saturation and then falls to a low value at saturation; this course corresponds roughly to our curve for the slowly cooled specimen. For annealed nickel,[18] on the other hand, the value of δ decreases continually as $(B-H)$ increases; this corresponds to our rapidly cooled specimen. What factors determine the shapes of the δ *vs.* $B-H$ curves is not now understood, but we expect that such an understanding will be helped by the separation of the losses into their components.

A calculation of macro-eddy-current losses in the rapidly cooled specimen (c) shows that at high intensities of magnetization these losses comprise the major portion of the total losses observed. The unusually high decrement of this specimen at $B=0$ is what would be expected from its high initial permeability of 5700, assuming the loss to be due mainly to micro-eddy-currents. The low decrement, 0.00053, of the unannealed specimen (a) in the unmagnetized condition may similarly be attributed to its low initial permeability, 54. The intermediate values of the decrements of the other specimens at $B=0$ are to be expected, but in view of the lack of the proper data necessary for a separation of micro-eddy-current and magnetomechanical hysteresis losses the different values of the decrement cannot be attributed with any assurance to differences in domain size or magnetomechanical hysteresis constant. As mentioned above we have already made some experiments to obtain the data necessary for a separation of these losses into their components.

We wish to express our indebtedness to Messrs. R. L. Wegel and R. F. Wick of these laboratories for the benefit of discussions concerning the methods of measurements of Young's modulus and damping, and to Professor W. F. Brown, Jr., of Princeton University for a discussion of eddy-current shielding in bars of square cross section.

[16] R. Becker and W. Döring, *Ferromagnetismus* (J. Springer, Berlin, 1939), p. 357.

[17] R. M. Bozorth and J. F. Dillinger, Phys. Rev. **35**, 733 (1930).

[18] S. Siegel and S. L. Quimby, Phys. Rev. **50**, 1165 (1936) and reference 14.