MAGNETOSTRICTION IN PERMALLOY

By L. W. McKeehan and P. P. Cioffi

Abstract

The *materials* studied comprised *iron, nickel,* and *permalloys* containing 46, 64, 74, 78, 80, 84 and 89 percent nickel. The method permitted simultaneous measurement of *magnetization* and *magnetostriction* in about 12 cm at the middle of a 40 cm wire, 1 mm in diameter, in an approximately uniform field not exceeding 40 gauss, and either with or without applied *tension* (within the elastic limit).

The *magnetostriction* was measured by a combination of a mechanical lever, an optical lever, a multiple slit and a photoelectric cell. The magnifying power of this combination, as used, was about 2×10^{6}, and magnetostrictive strains from 2×10^{-9} to 3×10^{-5} were detected and measured without changing the sensitivity.

The *magnetostriction-magnetization* curve has initial slope zero in all the cases studied. When the attainable field was sufficient for magnetic saturation the magnetostriction reached a limiting value. In *iron* there is evidence for the existence of a Villari reversal in fields too great to be attained in the apparatus. In *nickel* there is no sign of such reversal. In the *permalloys with more than 81 percent Ni* the magnetostriction is a *contraction.* In the *permalloys with less than 81 percent Ni* the magnetostriction is an *expansion.* The limiting values of magnetostriction, when plotted against chemical composition, fall on a smooth curve.

Tension increases magnetostrictive contraction and diminishes magnetostrictive expansion. It causes a reversal in the sign of magnetostriction in permalloy with 80 percent Ni, a small contraction preceding the final small expansion.

Introduction

The effects of tension upon the magnetization and hysteresis of permalloy[1] indicate with certainty that its magnetostriction in weak fields must change sign in the vicinity of 80 percent nickel and 20 percent iron. Honda and Kido,[2] who used cast ellipsoids, found such a change in this region of composition, but their experiments have nothing to say in regard to magnetostriction in weak fields. The present paper reports the results of simultaneous measurements of magnetization and magnetostriction, the latter by a new and precise method, in a series of well-annealed wires, including iron, nickel and permalloy in seven different compositions. The alloys contained, by analysis, in the form used, the following amounts of nickel in weight percent: 45.57, 64.44, 74.17, 78.07, 80.35, 84.41, 89.43. They have the same crystal structure (face-centered cubic) as nickel, the dimensions of

[1] Buckley, O. E., McKeehan, L. W., Phys. Rev. (2) **26** 261–273 (1925).
[2] Honda, K., Kido, K., Tohoku Univ. Sci. Rep. **9** 221–232 (1920).

the unit of structure increasing slightly as the nickel content diminishes.[3] In what follows the composition will be given only to the nearest percent. The iron and nickel wires were of comparable purity, cast from the same stock metals, and worked into wire in the same manner as the alloys. Nickel and permalloy wires were annealed for 20 hours in vacuum at 1200°C; the iron wire was kept at 1000°C for one hour and then at 850°C for two hours. During and after heat-treatment the wires were kept straight and free from over-strain of any kind.

The magnetostriction under no tension was measured for all the samples; the magnetostriction of the permalloys containing 74, 80 and 84 percent Ni was also measured under an applied tension of about 3600 lbs/in.^{2} (2.5×10^8 dyn/cm^2), due to a dead load of 4.5 lbs. hung at the lower end of the wire.

Apparatus and Method of Measurement

The principal parts of the apparatus are shown schematically in Fig. 1, which is distorted in order to show with equal clearness parts differing widely in dimensions. The wire under test was about 1 mm in diameter and 40 cm in length. It was hung vertically from a helical spring and was stretched, when desired, by loading its lower end. Magnetic fields were applied by passing currents through one or both of the two windings (#16 enameled wire) of a solenoid, 52 cm long and 3.1 cm in average diameter, coaxial with the sample and wound on the outside of a tubular glass jacket with two walls. These walls were silvered and the space between them was evacuated to reduce the radial flow of heat. The inside diameter of the jacket was 1.3 cm.

One of the windings of the solenoid was used for demagnetizing the specimen before each measurement of magnetization and magnetostriction.

The part of the wire in which the magnetostriction was measured was the middle 12 cm of its length. This was clamped at the top to the lower end of a rigidly supported brass sleeve and at the bottom to the upper end of a similar sleeve, the lower end of which projected from the magnetizing coil and rested on the shorter arm of a duralumin lever. The upper sleeve was 24 cm long, the lower, 21.5 cm. Both were of 1.6 mm inside, and 3.2 mm outside diameter, and were clamped onto the wire by small three-jawed brass chucks of the same outside diameter. The sleeves were slit longitudinally to reduce eddy currents. The upper sleeve was not fixed to its brass support until the wire and its supporting spring had been stretched by any applied load. (The

[3] McKeehan, L. W., Phys. Rev. (2) **21,** 402–407 (1923).

weight of the lower sleeve was balanced by the lever.) The helical spring then ensured that magnetostrictive strains in the upper part of the wire did not create appreciable differences in tension within it, above and below the plane of attachment of the upper chuck.

The duralumin lever was 22 cm long and its arms had the ratio 1 : 10. Its cross-section was rectangular, of width 3 mm and of height

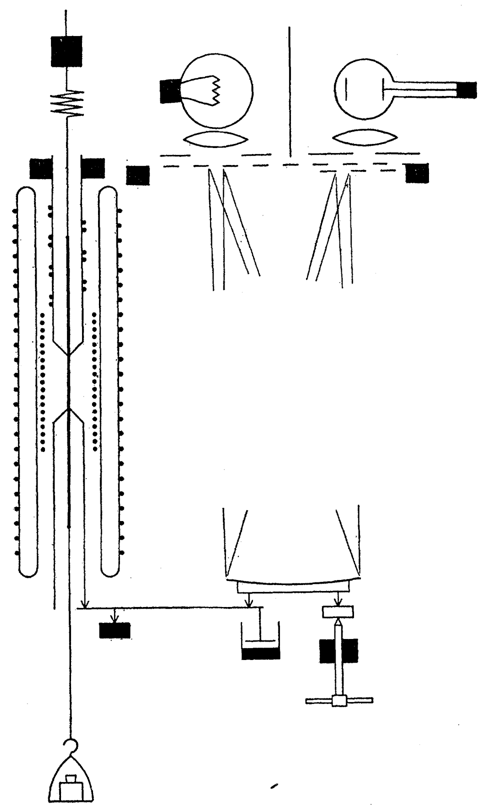

Fig. 1. Diagram of apparatus.

tapering from 5 mm to 2 mm. The lever rocked on an agate knife-edge, 2 cm long, resting on an agate plate. Its long arm had cemented on its top a slip of glass on which rested the free foot of an optical lever. It also carried, for mechanical damping, a plunger traveling freely in a dash-pot that could be filled with oil when especially sudden displacements were to be measured. Magnetostrictive displacements did not generally require the use of this dash-pot. The other two feet of the optical lever, on a line 0.794 cm from the free foot, rested in small glass cups on a brass arm which could be bent slightly by a stout screw in a more rigid member so as to adjust the height of the axis of tilt. One of the cups was set in the end of a set screw to permit leveling this axis.

The optical lever carried upon its nearly horizontal upper surface a selected concave glass mirror, 1.3 cm in diameter and with a radius of curvature of 1 meter, front-silvered in vacuum by evaporation. The mirror was stabilized by grinding the metal support to fit its back. A glass screen on which black lines 0.0508 cm wide were accurately engraved 0.0508 cm apart, was set horizontally one meter above the mirror and with its lines parallel to the axis of tilt. A small lens condensed the light, from a 14-volt gas-filled incandescent lamp with coiled tungsten filament, upon the screen so as to cover a circle about 1.5 cm in diameter and to form an image of the filament on the concave mirror. The mirror was then adjusted to project an image of the illuminated part of the screen onto an otherwise unilluminated part of the same screen. A lens set just above this image collected the transmitted light into a photoelectric cell connected through a dry-cell battery (70 volts) to a galvanometer.[4] The tilting of the optical lever caused the bright stripes of the image to travel across the equally-spaced transparent stripes of the screen. The change in the transmitted light was nearly proportional to the change in length of the section of wire between the two sleeves. The galvanometer (Leeds and Northrup, Type #2285, period on open circuit 7 sec) in series with the photoelectric cell was critically damped and adjusted to give a deflection of about 50 cm (at a distance of 120 cm) for the change from full transmission to full cut-off. An iris diaphram in the collecting system was used for this adjustment, its normal opening being such that the maximum transmission was practically independent of image position over a wide range. The lamp, operated on portable storage batteries. without series resistance, gave a sufficiently steady source of light, Under these conditions 1 mm on the scale of the galvanometer corresponded roughly to a total change in length of the object, in this case 12 cm of wire, of 4×10^{-8} cm. For changes in length greater than about 2×10^{-5} cm account had to be taken of the opposite variation of galvanometer deflection and length during successive half-millimeters of the motion of the image on the screen. Changes in length greater than about 4×10^{-4} cm caused such large displacements of the image that the photoelectric cell ceased properly to integrate the transmitted light, but this limit was not exceeded in the final measurements.

[4] The lamp and photoelectric cell were those used in these laboratories for the telephonic transmission of pictures. H. E. Ives, Bell System Tech. J. **5**, 320–336 (1926).

The multiple slit and photoelectric integrator are similar in principle to an arrangement used by Rankine[5] for detecting rapid vibrations. Their use in the manner here described has the effect of giving to the length-measuring galvanometer a nearly uniform scale, some 10 meters long, folded into a space of less than 50 cm.

The principal assembly of apparatus (corresponding to Fig. 1) was mounted on a two-inch oak plank hung vertically on a Julius suspension with damped springs.[6] A felt-lined cabinet standing on the floor and high enough to surround the suspended system further reduced the effects of air currents and other sources of mechanical and thermal disturbances. The galvanometer was separately suspended.

The length-measuring galvanometer was calibrated by propping up the long arm of the duralumin lever at a point a few centimeters from its bearing, and then allowing a succession of drops of oil, fed under constant pressure through a small nozzle, to fall into a pan so hung as to bend the free end of the lever. The interval between drops was so adjusted that the galvanometer index came to rest in each interval, permitting accurate reading of its position on the scale. The drops being of equal weight, and the greatest stress in the lever being well within its elastic limit, it could safely be assumed that the consecutive positions of the image on the screen (about 2×10^{-3} cm apart) were equally spaced. A representative calibration curve, obtained in this way, is shown in Fig. 2. The points are plotted as read, without any sort of smoothing. Along the upper edge of Fig. 2 four diagrams are placed which show how the image, as seen from the upper side of the screen, travels across the field of the photo-electric cell (the smaller circle of the diagrams) as the lever is bent. The diagrams correspond to the points on the calibration curve directly beneath them, but the number of stripes in the image has been reduced to make the changes in its appearance more conspicuous. The background, consisting of both opaque and transparent stripes, is shown black in these diagrams.

The relation between image position and reading on the galvanometer scale is nearly enough linear over about 85 percent of the total range on the scale, but optical defects cause a deviation from linearity near the positions corresponding to greatest and least transmission. This could be taken into account in the interpretation of scale readings in the affected regions, but it was better to avoid such readings by a method to be described below.

[5] Rankine, A. O., Proc. Phys. Soc. **31**, 242–264 (1919).
[6] Johnsrud, A. L., J. O. S. A. & R. S. I. **10**, 609–11 (1925).

Since heat is generated in the wire and its attachments by the eddy currents set up during changes in magnetization and since a rise of temperature of only 0.001°C causes thermal expansion (in the 12 cm of wire alone) sufficient to change the galvanometer reading by about 50 mm, the drift due to imperfect thermal equilibrium within the nearly heat-tight enclosure would have been troublesome. To eliminate drift, a non-inductive winding was imbedded in the upper brass sleeve, and such a current—a few milli-amperes—was passed through this winding, that its equilibrium temperature was raised a few hundredths of a degree. This current was then regulated, just before each reading, until the drift was compensated. This process was made nearly instantaneous by reducing the thermal capacity of the sleeve and its winding to

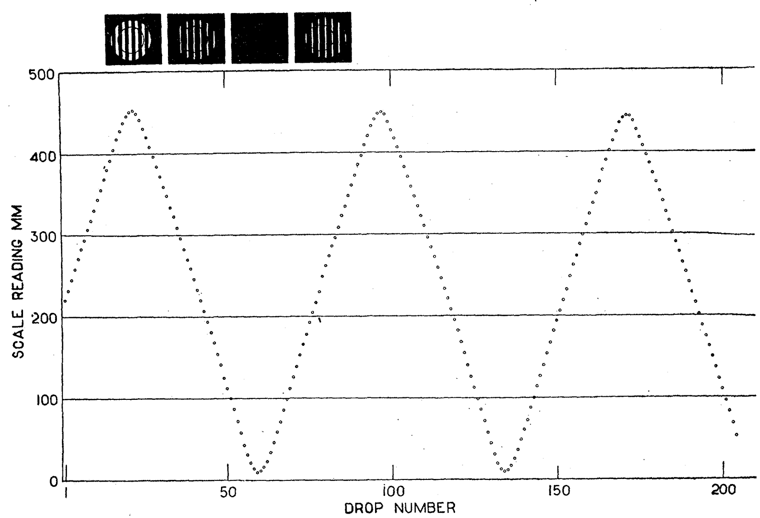

Fig. 2. Representative calibration curve.

the smallest practicable value. In the absence of magnetic changes it was possible in this way for a practiced observer to keep the galvanometer index steady within a range of one millimeter as long as desired and deflections could be taken from a zero chosen, for greater accuracy so that both the initial and final readings fell within the linear part of the scale. The same artifice made it convenient to check the constancy of the maximum photoelectric current, i. e. the constancy of the lamp and photoelectric cell, before each reading, by varying the length of the system slowly through a value corresponding to maximum galvanometer deflection (upper turning-point). The sign of a change in length was determined by noting in which direction an increase in the drift-correcting current—corresponding to increase in length—moved the galvanometer index. The number of maxima and minima traversed in a large change in length was sometimes checked by making the change in applied field take place so slowly that the galvanometer had time to go through the successive turning-points. In all cases where the initial and final readings lay between different pairs of turning-points the upper turning-point was determined after, as well as before, the

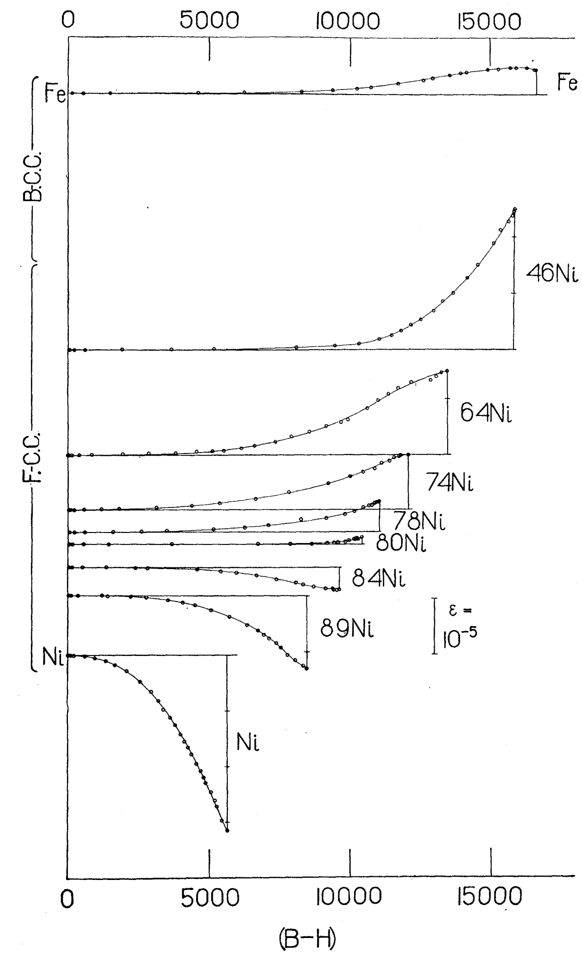

Fig. 3. Dependence of the relative change in length upon the ferric induction.

deflection occurred. The lower turning-point, it should be noted, was practically independent of the state of the optical and photoelectric systems.

Changes in magnetization were measured in the usual way.[7] The search-coil, mounted in the jacket at the center of the length of the

[7] Cioffi, P. P., J.O.S.A. & R.S.I. **9**, 53–60 (1924).

specimen, was wound on 15.2 cm of the length of a hard rubber spool 17 cm long, of 3.6 mm inside, and 11 mm outside diameter. It comprised 17,735 turns of #40 single-silk-covered wire, and the maximum sensitivity of the ballistic galvanometer (Leeds and Northrup, Type 2285) in series with it was such that small changes in $(B-H)$ were measured within about one gauss.

The compensation of the vertical component of the earth's magnetic field was frequently checked, by noting the equality of changes in magnetization for equal positive and negative field increments.[8] The uncompensated poles at the ends of the specimen made the field within it less than the applied field. The true magnetization-field curves were accordingly determined, in advance, in shielded apparatus[1] wherein the pole effect was eliminated, and it was assumed that at the same values of B the values of H within the sample in the unshielded apparatus were those more accurately determined in the shielded apparatus. The correction to be subtracted from the applied field was, over most of the range in $(B-H)$ for each pecimen, $(B-H)\times 40\times 10^{-6}$. It was determined by experiment that when a non-magnetic wire was tested there was no change in length due to the application of magnetic fields and, in other experiments, that the forces on the ends of a magnetic wire due to the unavoidable non-uniformity of the magnetic fields near its ends did not change the length of a non-magnetic segment between the chucks.

Results

The dependence of the relative change in length, i. e. the strain, ε, upon the ferric induction, $(B-H)$, is shown, for all unstretched specimens, in Fig. 3. The scale for $(B-H)$, which is abscissa, is common to all the curves of Fig. 3, but the zero ordinate for each curve is set at a height which depends upon the composition of the specimen.

The range $/\varepsilon$ was so great, and the precision in its measurement so high, that graphical presentation, as in Fig. 3, cannot easily do justice to the data. Representative data and calculations for a few cases are therefore presented in Table I.

The applied field was carried to an upper limit of about 40 gauss. This was sufficient to saturate all the permalloys, but was insufficient to saturate either nickel or iron alone. The magnetostrictive strain was found to approach a limiting, or saturation, value whenever magnetic saturation was effected. Fig. 4 gives ε as a function of H

[8] McKeehan, L. W., Cioffi, P. P., J.O.S.A. & R.S.I. **9**, 479–485 (1924).

TABLE I

Illustrative data and calculated quantities

i, magnetizing current, amperes; H, magnetizing field, gauss; d, ballistic galvanometer deflection, mm; $(B-H)$, magnetization, gauss; δ, length-measuring galvanometer deflection, mm; n, number of turning-points traversed; ε, magnetostrictive strain (cm/cm), A horizontal row of dashes calls attention to the omission of a series of points from the table.

Material, and region considered.	i	H	d	$(B-H)$	δ	n	ε
Ni, Initial region and last point.	0.005	0.044	4.0	11	0	0	0
	0.010	0.089	8.3	22	0	0	0
	0.020	0.177	20.6	58	−1	0	-3×10^{-9}
	0.030	0.263	59.	114	−2	0	-7×10^{-9}
	0.040	0.349	70.	214	−12	0	-41×10^{-9}
	0.060	0.513	188.	603	−66	0	-230×10^{-9}
	———	———	———	———	———	—	———
	3.50	31.3	67.3*	5630	−206	19	-31620×10^{-9}
80 Ni (without tension), initial region and last point.	0.002	0.016	11.6	39	0	0	0
	0.006	0.047	47.7	163	0	0	0
	0.012	0.085	163.	564	0	0	0
	0.020	0.121	56.8*	1440	0	0	0
	0.040	0.210	147.	3690	0	0	0
	0.080	0.447	58.2*	6720	+2	0	$+7\times10^{-9}$
	———	———	———	———	———	—	———
	4.48	40.0	111.1	10400	+311	0	$+1150\times10^{-9}$
80 Ni (with tension) first point, reversal region, and last point.	0.010	0.076	96	329	0	0	0
	———	———	———	———	———	—	———
	0.200	1.63	75.5*	8680	−24	0	-88×10^{-9}
	0.300	2.68	82	9390	−23	0	-84×10^{-9}
	0.350	3.13	83.2	9480	−14	0	-51×10^{-9}
	0.400	3.58	84	9560	−7	0	-26×10^{-9}
	0.500	4.48	86	9730	+12	0	$+44\times10^{-9}$
	0.600	5.38	88	9920	+29	0	$+107\times10^{-9}$
	———	———	———	———	———	—	———
	4.57	40.9	112.2	10480	+173	0	$+661\times10^{-9}$
Fe, maximum expansion.	0.050	0.441	60.5	184	0	0	0
	———	———	———	———	———	—	———
	1.00	8.95	131.6	14920	+250	2	$+426\times10^{-9}$
	1.40	12.54	137.0	15300	+288	2	$+440\times10^{-9}$
	1.90	17.00	142.9	15720	+333	2	$+460\times10^{-9}$
	2.46	22.0	147.4	15940	+314	2	$+452\times10^{-9}$
	3.08	27.6	153.8	16320	+311	2	$+451\times10^{-9}$
	3.64	32.6	158.8	16580	+276	2	$+436\times10^{-9}$
	4.40	39.4	162.8	16650	+228	2	$+420\times10^{-9}$

* Change in sensitivity of ballistic galvanometer.

(corrected) for a few cases only. Fig. 5 shows how the greatest observed strains depended upon the composition.

The results for magnetostriction in stretched permalloys are shown in Fig. 6, in which, for comparison, have been included also the results for the same wires when unstretched. The scale for ε has been made much more open in Fig. 6 than in Fig. 3. In the case of permalloy with 80 percent Ni curves have been drawn through points (dots) with ordinates ten times greater than those plotted on the standard scale,

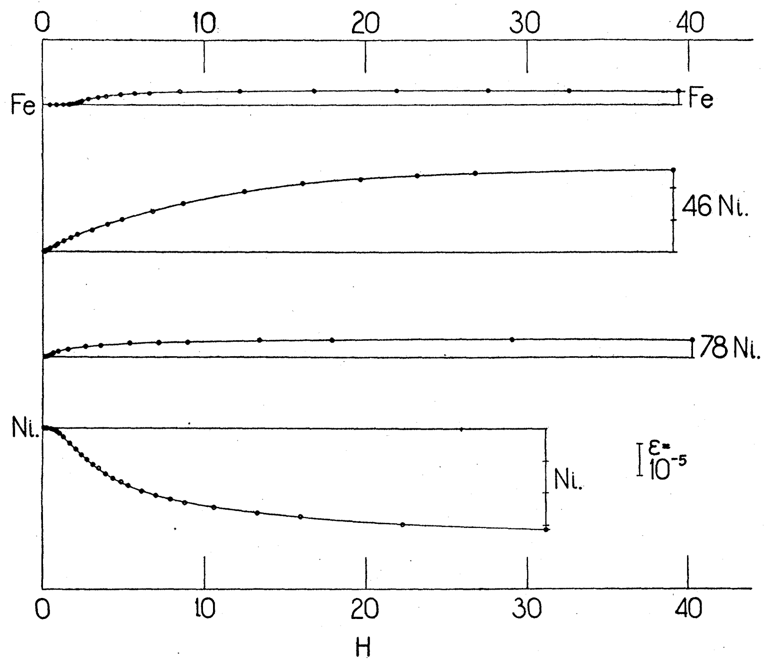

Fig. 4. The strain ε as a function of magnetic field strength.

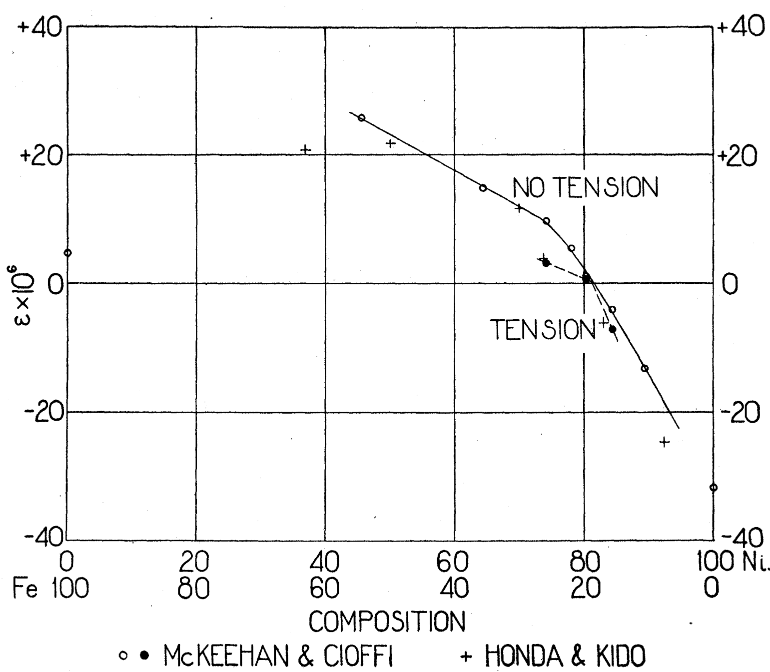

Fig. 5. Dependence of the greatest observed strains upon composition.

in order to show more clearly the changes in ε produced by tension. A still larger scale for ε would have been justified by the precision of the readings (cf. Table I).

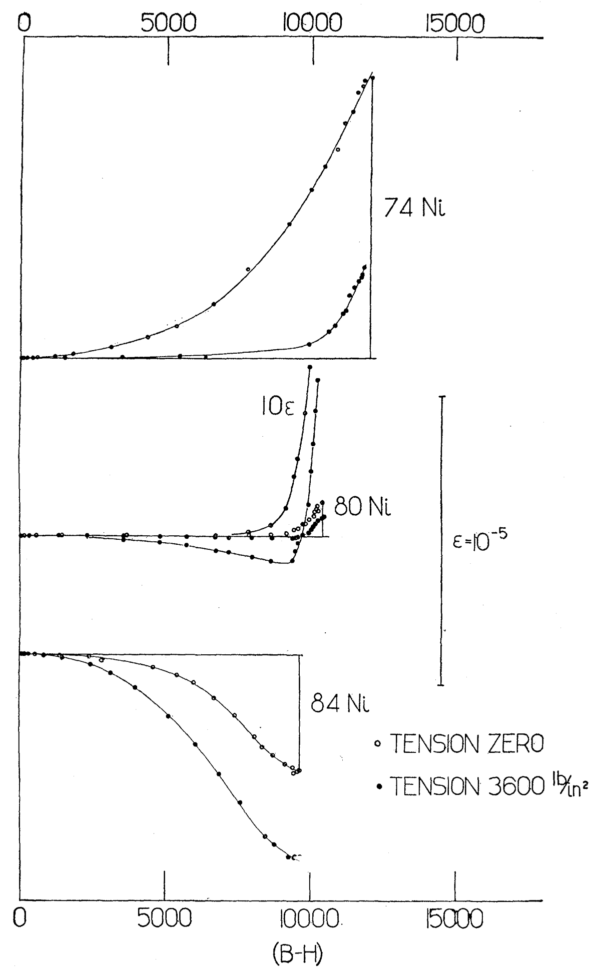

Fig. 6. Showing results for magnetostriction in stretched permalloys.

Discussion of Results

The greatest magnetostrictive strains recorded by Honda and Kido[2] for alloys in the range of compositions here studied have been plotted in Fig. 5. The lowest field applied in their experiments was 10.5 gauss, the highest, 590.5 gauss. The discrepancies between our results and theirs are not greater than might be expected from the differences in methods of preparation and experiment.

The behavior of iron, as far as it could be studied in our apparatus, is similar to that usually reported in having a maximum expansion followed by lower values at higher magnetizations.

The theoretical bearings of the experimental results here obtained, and others, are discussed by one of us in the following paper.[9]

We desire to express our appreciation of the alertness and accuracy of Mr. R. H. Raguse as second observer in all the experiments here described.

Bell Telephone Laboratories, Inc.,
New York City.
April 17, 1926.

[9] McKeehan, L. W., Phys. Rev. (2), **28** 158–166 (1926).