# ELECTRICAL RESISTANCE OF NICKEL AND PERMALLOY WIRES AS AFFECTED BY LONGITUDINAL MAGNETIZATION AND TENSION

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Abstract

The changes in the electrical resistance of ferromagnetic metals in magnetic fields and under mechanical stresses are abnormal in comparison with such changes in non-ferromagnetic metals. Published results for nickel and nickel-rich alloys, reviewed in detail, show wider diversity than can be ascribed to accident. A full bibliography is included.

Simple cases of these magneto-resistance and elasto-resistance effects have been studied in permalloys containing from 45 to 90 percent nickel. The results of two series of experiments, in 1923 and 1929, are presented, and show that both effects have, in these ferromagnetic alloys, the same origin. This common origin can be considered as the orientation, by one means or the other, of atomic magnetic axes associated in each atom with mechanical asymmetry.

The connection between these resistance effects and magnetostriction is emphasized. Conclusions are drawn as to the kinds of re-orientation involved in magnetizing and as to the relative importance in the observable effects of intra-atomic and inter-atomic magnetic fields. Questions for further experiment are raised.

## Introduction

THE changes in the electrical resistance of solid metallic conductors when subjected to the action of magnetic fields have attracted the attention of one hundred and twenty-eight investigators. The changes in resistance of such conductors when compressed or distorted have been measured or discussed by ninety-one. Thirteen names appear on both lists, so that no novelty can here be claimed for the idea that there is an intimate connection between the two effects. Recent improvements in magnetic materials have, however, made a study of this connection much easier and have suggested that in it may lie important clues for solving the problem of ferromagnetism. The new data collected in such a study, and reported below in some detail, make it interesting to review previous data of comparable character, the discrepancies in which have become more puzzling as the technique of measurement has improved.

### Magneto-Resistance.

On the basis of their changes in electrical resistance when placed in a strong magnetic field, metals and alloys may be assigned to one or the other of two groups. Members of the first and more numerous group increase in resistance whatever may be the relative directions of the current, $i$ and the applied magnetic field, $H$. Members of the second group increase in resistance if $i$ and $H$ are parallel, decrease if $i$ and $H$ are perpendicular. One observer[1] has reported *decrease* in resistance for both parallelism and perpendicularity of $i$ and $H$ in copper-rich alloys with low temperature coefficients of resistance, *e.g.* constantan. If confirmed this necessitates a third group.

Members of the second group show relatively much larger changes of resistance than those of the first group for values of $H$ of the order of $10^3$ gauss, and relatively much smaller changes for values of $H$ of the order of $10^5$ gauss.[2] All members of the second group are ferromagnetic, and no ferromagnetics occur in the first group. The magneto-resistance effect in non-ferromagnetics is only measurable with accuracy in very intense magnetic fields at room temperature,[2] or in somewhat less intense fields at low temperatures.[3] The change in resistance depends simply upon $H$, though the exact form of dependence is not yet agreed upon.[4] In ferromagnetics, on the other hand, the effect attains its limit in fields of such moderate intensity that the whole course of the phenomenon has been accessible to investigation for a long time. The diversity of reported results is surprizing and deserves more consideration than it has hitherto received.

**Elasto-Resistance.**

Ferromagnetic metals are also sharply distinguishable from non-ferromagnetics on the basis of the changes in resistance which they temporarily suffer during elastic deformation. Many experiments on these elasto-resistance effects are difficult to interpret because of poorly defined initial conditions or inhomogeneity of applied stresses. In general, however, the resistance in ferromagnetics is more sensitive to non-isotropic stresses[5] and less simply related to the intensity of stress, than in non-ferromagnetics.

## Review of Previous Work

Among ferromagnetic metals and alloys, nickel and nickel-rich alloys are especially interesting in this connection because of the relative simplicity they offer. Nickel is the only ferromagnetic element that has no phase change below its melting point.[6] This means, for one thing, that its physical condition is little liable to alteration by thermal treatment. Nickel is also superior to iron for studies on polycrystalline specimens because, as its magnetostriction[7] suggested, and as has since been demonstrated,[8] the magnitude of the longitudinal magneto-resistance effect—$i$ and $H$ parallel—is nearly the same for all directions in a monocrystalline specimen. This means that polycrystalline nickel, and nickel-rich alloys over the appropriate

[1] J. Obata, Bibliography Item 29.

[2] P. L. Kapitza, Proc. Roy. Soc. **A123**, 292–341, 342–372 (1929).

[3] W. Meissner, H. Scheffers, Phys. Zeits. **30**, 827–836 (1929).

[4] W. Meissner, H. Scheffers, Naturwiss. **18**, 110–113 (1930); P. L. Kapitza, Proc. Roy. Soc. **A126**, 683–695 (1930).

[5] As will be shown below, permalloy of critical composition—with about 81 percent nickel—is exceptional in this respect.

[6] S. B. Hendricks, M. E. Jefferson, J. F. Shultz, Zeits. f. Krist. **73**, 376–380 (1930).

[7] Y. Mashiyama, Sci. Rep. Tohoku Imp. Univ. [I] **17**, 945–961 (1928).

[8] S. Kaya, Bibliography Item 35.

range of composition in each system, should, except for such minor differences as may be due to preferred orientation of the crystallites, behave like monocrystalline metal. The corresponding expectancy does not exist in the case of polycrystalline iron, since the longitudinal effect in iron monocrystals[9] differs widely in magnitude for crystallographically different directions. What has so far been reported regarding the magnetostriction of cobalt monocrystals,[10] and the conditions for the stability of hexagonal cobalt,[11] make it likely that anisotropy will modify the magneto-resistance effect in polycrystalline cobalt even more than in polycrystalline iron.

For the reasons just presented it seems best to limit the review of previous work to that which deals with nickel and nickel-rich alloys at room temperature or lower. It will also be necessary to omit all results on the transverse magneto-resistance effect, since the transverse effect is peculiarly subject to errors caused by magnetization in undesired directions. In studies on the longitudinal effect errors due to failure of exact parallelism of $i$ and $H$ are serious only in the highest fields and the maximum increase in resistance, though reached in less than the greatest applied field, and followed by a steady decrease in resistance in greater fields, is only slightly less than for perfect alignment.[12] As regards elasto-resistance the review will consider only the effects of tension, since tensile stress is the only homogeneous non-isotropic stress that can easily be applied, and is therefore the type of stress selected in the experiments here to be reported. Even with these rather drastic limitations there remain about forty papers to be considered. The use of tables and graphs thus appears necessary.

TABLE I-A. *Longitudinal magneto-resistance in nickel.*[13]

| | Specimen[14] | Tension kg/mm² | $H_{max}$ gauss | $H$ for $-(\Delta R/R)_{max}$ gauss | $-(\Delta R/R)_{max}$ percent | Figures |
|---|---|---|---|---|---|---|
| 1 | Prism 0.30×1.32×3.0 cm³ | — | — | — | 0.7 | — |
| 2A | Rod 0.7 cm diam. as cast | — | 80 | 80 | 0.45 | 1 |
| 2B | 0.105 cm diam. annealed | — | 42 | 42 | 0.45 | 1, 3 |
| 2C | same | 2.3 | 42 | 42 | 0.34 | 3 |
| 2D | same | 6.9 | 42 | 42 | 0.29 | 3 |
| 3 | 0.033 cm diam. | — | — | — | —[15] | — |
| 4 | Electrodeposited film | — | — | — | 1.5 | — |
| 5A | ditto | — | 1376 | 1376 | 2.023 | — |
| 5B | ditto | — | 1211 | 1211 | 1.928 | 2 |
| 5C | ditto | — | 1410 | 1410 | 1.643 | 2 |
| 5D | ditto | — | 1361 | 1361 | 1.139 | 2 |
| 6A | 0.01551 cm diam. unannealed | — | 167 | 167 | 1.29 | 2 |

[9] W. L. Webster, Proc. Roy. Soc. **A113**, 196–207 (1926).

[10] Z. Nishiyama, Sci. Rep. Tohoku Imp. Univ. [I] **18**, 341–357 (1929).

[11] H. Masumoto, Sci. Rep. Tohoku Imp. Univ. [I] **15**, 449–477 (1926); A. B. Cardwell, Proc. Nat. Acad. Sci. **15**, 544–551 (1929); *loc. cit.*[6]

[12] W. M. Jones, J. E. Malam, Bibliography Item 26.

[13] Especially in the earlier work the nickel may have been far from pure.

[14] The number designating a specimen refers to the item in the Bibliography wherein the data occur. A letter is added to distinguish the several specimens, or states of one specimen, covered by one numerical reference. Except as noted, specimens were drawn wires.

[15] The specimen was coiled and placed in a uniform field so that the purely longitudinal effect was not measured. As far as the data go they are in qualitative agreement with those of Tomlinson.

TABLE I-A (*continued*)

| | Specimen | Tension kg/mm² | $H_{max}$ gauss | $H$ for $-(\Delta R/R)_{max}$ gauss | $-(\Delta R/R)_{max}$ percent | Figures |
|---|---|---|---|---|---|---|
| 6B | 0.02563 cm diam. annealed | — | 130 | 130 | 2.04 | 2 |
| 7A | Diam. not given | — | 4130 | 2280 | 1.23 | — |
| 7B | 0.1 cm diam. | — | 170.4 | 170.4 | 1.77 | — |
| 8A | 0.102 cm diam. unannealed | — | 738.7 | 738.7 | 1.500 | — |
| 8B | 0.047 cm diam. annealed | — | 602.5 | 602.5 | 1.331 | — |
| 8C | Strip 0.027×0.30 cm² | — | 671.0 | 671.0 | 1.431 | — |
| 8D | Strip 0.027×0.15 cm² | — | 700.6 | 700.6 | 1.296 | — |
| 9A | 0.102 cm diam. unannealed | — | 64 | 64 | 0.514 | 1 |
| 9B | 0.047 cm diam. annealed | — | 63.3 | 63.3 | 0.683 | 1 |
| 9C | Strip 0.027×0.30 cm² | — | 67.2 | 67.2 | 0.687 | 1 |
| 11 | 0.04 cm diam. | — | 3300 | 3300 | 1.439 | 2 |
| 12A | 0.0765 cm diam. | — | 165 | 165 | 0.72 | 1 |
| 12B | ditto | — | 450 | 450 | 1.29 | 2 |
| 12C | ditto | — | 11000 | 790 | 1.70 | — |
| 12D | 0.0200 cm diam. | — | 18000 | 2000 | 1.56 | — |
| 13 | Diam. not given | — | 24000 | 1500 | 1.5 | — |
| 14A | 0.012 cm diam. | — | 420 | 420 | 0.97 | 2, 3 |
| 14B | same | 4.4 | 420 | 420 | 1.09 | — |
| 14C | same | 8.8 | 370 | 370 | 1.10 | — |
| 14D | same | 26.6[16] | 320 | 320 | 1.05 | 3 |
| 14E | same | 44.2[16] | 425 | 425 | 1.27 | 3 |
| 14F | same | 62.0[16] | 425 | 425 | 1.08 | 3 |
| 15 | 0.013 cm diam. | — | 69.5 | 69.5 | 0.755 | 1 |
| 16A | 0.035 cm diam. unannealed | — | 785 | 785 | 1.90 | 2 |
| 16B | 0.035 cm diam. annealed | — | 785 | 785 | 1.42 | 2, 3 |
| 16C | 0.021 cm diam. unannealed | — | 560 | 560 | 2.14 | 2 |
| 16D | 0.014 cm diam. unannealed | — | 785 | 785 | 3.07 | 2 |
| 16E | 0.014 cm diam. annealed | — | 785 | 785 | 1.97 | 2 |
| 16K | 0.035 cm diam. annealed | 2.18 | 795 | 795 | 1.53 | — |
| 16L | same | 5.44 | 795 | 795 | 1.66 | — |
| 16M | same | 10.9 | 800 | 800 | 1.87 | 3 |
| 16N | same | 21.8 | 800 | 800 | 2.36 | 3 |
| 16P | same | 32.7[17] | 800 | 800 | 2.25 | 3 |
| 17 | Diam. not given | — | 34 | 34 | 1.040 | 1 |
| 18A | Diam. not given | — | 900 | 900 | 1.60 | 2 |
| 20 | 0.0035 cm diam. at −190°C | — | 3000 | 3000 | 5.5 | — |
| 21A | 0.050 cm diam. | — | 2200 | 1250 | 2.35 | 2 |
| 21B | 0.017 cm diam. | — | 9300 | 4000 | 1.26 | 2 |
| 22A | 0.00206 cm diam. | — | 29000 | 2800 | 1.462 | — |
| 22B | 0.00159 cm diam. | — | 28500 | 2800 | 1.418 | 2 |
| 23 | "Thin" strip 2.1 cm wide | — | 57 | 57 | 0.64 | 1 |
| 24A | 0.0425 cm diam. annealed | 1.77 | 1000 | 1000 | 1.46 | 3 |
| 24B | same | 8.8 | 1000 | 1000 | 1.86 | — |
| 24C | same | 17.7 | 1000 | 1000 | 2.20 | 3 |
| 24D | same | 26.2[17] | 1000 | 1000 | 2.23 | — |
| 24E | same | 31.9[17] | 1000 | 1000 | 2.15 | 3 |
| 25 | 0.0015 cm diam. | — | 2600 | 1000 | 1.30 | 2 |
| 26 | 0.00206 cm diam. | — | 14500 | 3000 | 2.347 | 2 |
| 27 | 0.022 cm diam. | — | 1900 | 1900 | 0.90 | 2 |
| 29A | Diam. not given | — | 15400 | 3500 | 1.22 | 2 |
| 31A | 0.15 cm diam. | — | 1390 | 1390 | 1.77 | 2, 3 |
| 31B | same | 12.9 | 1610 | 1610 | 2.46 | 3 |
| 31C | same | 26.1[17] | >1700 | 1700 | 2.60 | 3 |
| 33 | 0.125 cm diam. annealed at 950°C | — | 1100 | 450 | 1.48 | 2 |
| 35A | Polycrystalline prism 0.125×0.125×2 cm³ | — | 1387 | 539 | 2.16 | 2 |
| 35B | <100> prism 0.125×0.125×2.6 cm³ | — | 1415 | 943 | 1.97 | 2 |
| 35C | <110> prism 0.130×0.155×2.2 cm³ | — | 1375 | 903 | 2.33 | 2 |
| 35D | <111> prism 0.090×0.113×1.3 cm³ | — | 1368 | 520 | 2.41 | 2 |
| 37 | 0.0051 cm diam. | — | 180 | 180 | 0.46 | 1 |
| 39 | Diam. not given. 0.6 percent Mn | — | 500 | 500 | 1.34 | — |
| 40 | 0.02 cm diam. | — | 255 | 255 | 1.15 | — |

[16] Probably above the elastic limit for annealed nickel. The smooth progression of the curves indicates therefore that the wire was not annealed.

[17] Probably above the elastic limit for annealed nickel.

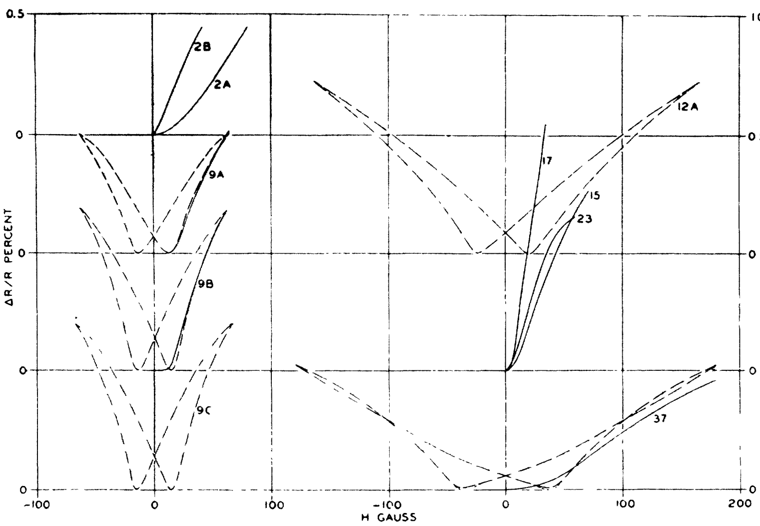


Fig. 1. Longitudinal magneto-resistance in nickel. Previously published results.

TABLE I-B. *Longitudinal magneto-resistance in nickel alloys.*

| | Specimen[14] | Tension kg/mm$^2$ | $H_{max}$ gauss | $H$ for gauss | $-(\Delta R/R)_{max}$ percent | Figure |
|---|---|---|---|---|---|---|
| 16F | Platinite [Ni 47 Fe 53?] 0.035 cm diam. unannealed | — | 580 | 500 | 0.31 | 4 |
| 16G | ditto annealed | — | 740 | 405 | 0.028 | — |
| 16H | Nickel-steel [Ni 27 Fe 73?] diam. not given | — | 800 | 80 | 0.0045 | — |
| 16J | Rheostene [Ni 26 Fe 74?] diam. not given | — | — | — | 0.0018 | — |
| 16Q | Platinite [Ni 47 Fe 53?] 0.035 cm diam. unannealed | 18.5 | 630 | 300 | 0.16 | 4 |
| 16R | same | 22.9 | 770 | 300 | 0.13 | — |
| 18B | Ni 24 Fe 76 Diam. not given | — | 800 | 300 | 0.06 | — |
| 18C | Ni 27.9 Fe 72.1 Diam. not given | — | 800 | 300 | 0.0065 | — |
| 18D | Ni 35.5 Fe 64.5 Diam. not given | — | 800 | 300 | 0.08 | — |
| 18E | Ni 40 Fe 60 Diam. not given | — | 800 | 300 | 0.14 | — |
| 18F | Ni 44 Fe 56 Diam. not given | — | 800 | 300 | 0.155 | 4 |
| 18G | Ni 48.7 Fe 51.3 Diam. not given | — | 800 | 300 | 0.23 | 4 |
| 18H | Ni 57 Fe 43 Diam. not given | — | 800 | 350 | 0.46 | 4 |
| 18J | Ni 70 Fe 30 Diam. not given | — | 800 | 350 | 0.72 | 4 |
| 24F | Monel, Ni 68 Cu 29.5 Fe 1.5 Mn 1 unannealed. Diam. not given | 3.95 | 250 | 100 | 0.164 | 4 |
| 24G | same | 13.8 | 250 | 150 | 0.226 | — |
| 24H | same | 23.7 | 250 | 175 | 0.246 | 4 |
| 24J | same | 33.6 | 250 | 200 | 0.250 | — |
| 24K | Monel, Ni 68 Cu 29.5 Fe 1.5 Mn 1 annealed. Diam. not given | 3.95 | 250 | 75 | 0.166 | 4 |
| 24L | same | 13.8 | 250 | 100 | 0.185 | — |
| 24M | same | 23.7 | 250 | 125 | 0.192 | 4 |
| 24N | same | 33.6 | 250 | 175 | 0.194 | — |
| 29B | Ni 72.86 Fe 20.09 Mn 7.04. Diam not given | — | 20000 | — | −0.059[18] | — |
| 29C | Ni 56.31 Fe 25.43 Cr 15.57 Mn 3.19. Diam. not given | — | 1300 | 600 | 0.035 | — |
| 29D | Ni 58.30 Fe 22.28 Cr 15.21 Mn 2.60 | — | 1200 | 500 | 0.056 | — |

[18] Probably in error, as this composition is ferromagnetic and should give a positive value for $\Delta R/R$.

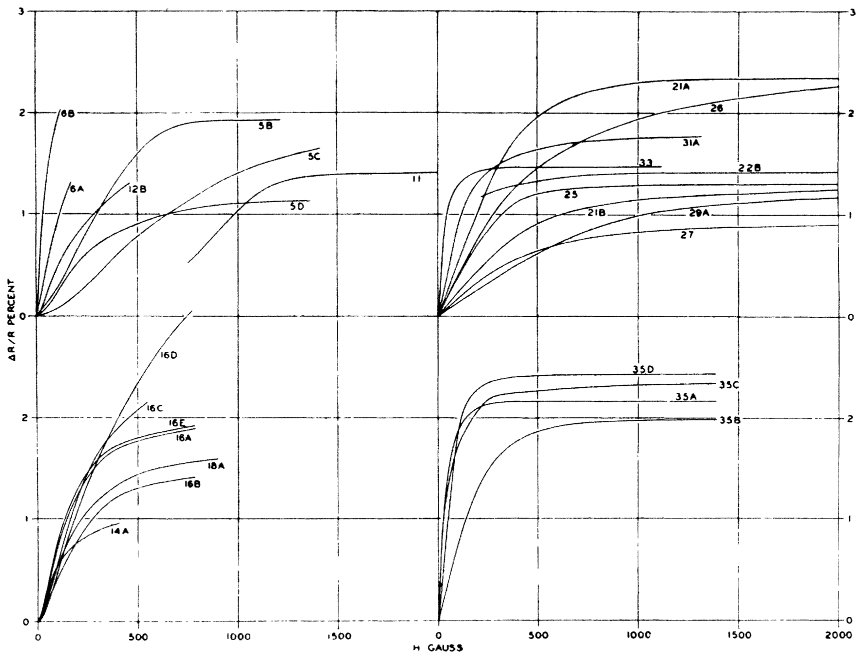


Fig. 2. Longitudinal magneto-resistance in nickel. Presiously published results.

TABLE II. *Elasto-resistance in nickel*[13] *under tension.*

| | Specimen[14] | $T_{max}$ kg/mm$^2$ | $T$ for kg/mm$^2$ | $-(-\Delta R/R)_{max}$ percent | Figure |
|---|---|---|---|---|---|
| 2E | 0.086 cm diam. annealed. Cyclic state | 27.4 | 13 | 0.420 | 5 |
| 2F | same | 30.8 | 13 | 0.415 | — |
| 2G | same | 34.2 | 15 | 0.351 | — |
| 2H | same | 37.7 | 15 | 0.321 | — |
| 2J | same | 41.1 | 15.5 | 0.292 | 5 |
| 2K | 0.078 cm diam. annealed. Cyclic state | 37.6 | 16.5 | 0.500 | 5 |
| 2L | same after 25 kg/mm$^2$ at 100°C | 37.6 | 19.5 | 0.514 | — |
| 10A | 0.0251 cm diam. unannealed | 23 | 18 | 0.105[19] | 5 |
| 10B | same. Later | 24 | 14 | 0.074[19] | 5 |
| 19A | 0.024 cm diam. Loading | 42 | 28 | 0.050 | 5 |
| 19B | same. Unloading | 42 | 14 | 0.055 | 5 |
| 28A | 0.0259 cm diam. Loading | 15.5 | 11.0 | 1.68x[20] | 6 |
| 28B | same. Unloading | 15.5 | 9.5 | 1.76x[20] | 6 |
| 28C | same. Loading | 17.6 | 9.5 | 2.12x[20] | 6 |
| 28D | same. Unloading | 17.6 | 8.5 | 2.00x[20] | 6 |
| 28E | same. Loading | 18.0 | 9.5 | 1.76x[20] | 6 |
| 28F | same. Unloading | 18.0 | 8.5 | 1.28x[20] | 6 |
| 30A | 0.0129 cm diam. annealed. Loading at 0°C | 19.0 | 17.1 | 0.157 | 5 |
| 30B | same. Unloading at 0°C | 19.0 | 14.3 | 0.173 | 5 |
| 32 | Cast rod 0.317 cm diam. annealed | 19 | 19 | 0.48 | — |
| 34 | Strip 0.012×1.25 cm$^2$ | 3.78 | 3.78 | 0.54 | — |
| 36 | 0.056 cm diam. | — | — | 0.8 | — |
| 38 | 0.046 cm diam. | — | — | —[21] | — |

[19] Referred to initial state with 10 kg/mm$^2$.

[20] Referred to initial state with 3.8 kg/mm$^2$ and expressed in arbitrary units not convertible into percent by means of reported data.

[21] Reported data show a minimum in $R$ but do not permit calculation of either $T$ or $\Delta R/R$.

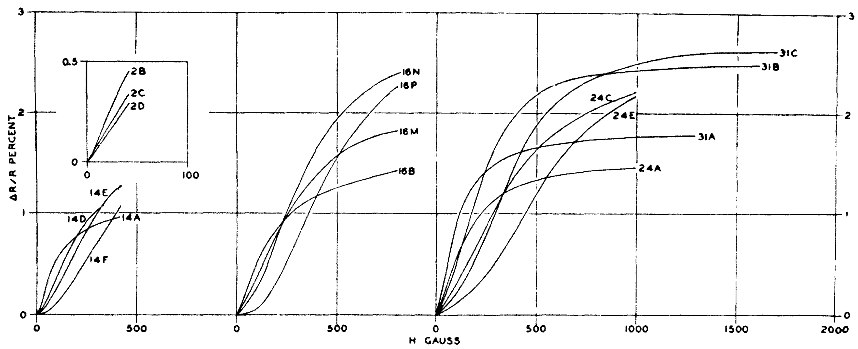


Fig. 3. Effect of tension on longitudinal magneto-resistance in nickel. Previously published results.

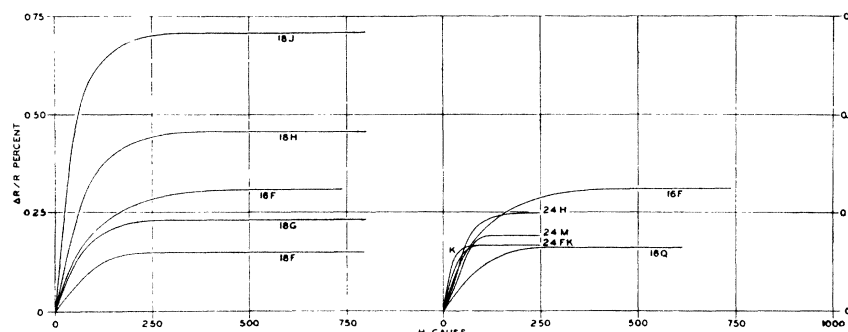


Fig. 4. Longitudinal magneto-resistance in nickel-iron alloys and effect of tension thereon. Previously published results.

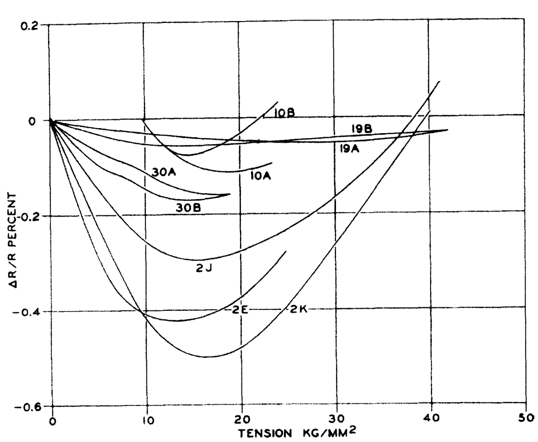


Fig. 5. Elasto-resistance in nickel for tension. Previously published results.

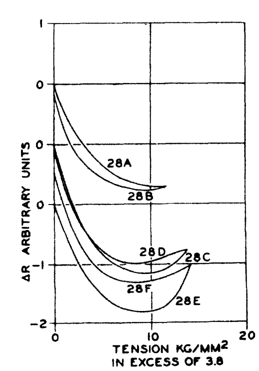


Fig. 6. Elasto-resistance in nickel under tension, after Nobile.

Tables I and II summarize the magneto-resistance and elasto-resistance data so far published. Figures 1 to 6 present curves selected to show the wide range of the reported results for nickel and a few nickel alloys. Many of these curves have been plotted from tables and are here presented for the first time in graphical form.[22] No effort has been made to distinguish those few sets of data in which correction has been made for the self-demagnetizing field. Except for short thick specimens of high magnetic permeability this correction would affect the appearance of the curves but little. Certain results of particular significance will be referred to in the discussion of the new material reported below.

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[22] Curve 2B has been drawn on the assumption that the value for $\Delta R/RH$ given by Tomlinson for annealed nickel in his Table XXIII is that for a specimen earlier described for which only relative values of $\Delta R/R$ are cited.

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**Comments on Bibliography.**

Tomlinson's work on elasto-resistance (Item 2) is not strictly comparable with later work because he usually accomodated a wire to the maximum load he intended to apply, that is, he repeatedly loaded and unloaded the wire until its resistance changes became cyclic. A wire so treated does not, if the range of stress is more than a few kg/mm$^2$, retain its initial properties.

Goldhammer (Items 4, 5 and 6) was the first to observe that there was a remanent magneto-resistance, and introduced great improvements in the control of temperature and in the method of making measurements. He attempted to prove that

$$R = R_0 + AI^2$$

where $R_0$ is the resistance of an unmagnetized wire, $I$ its magnetization, and $A$ a constant. Even his own data show this relation to be inexact. His last and most important paper appeared only in Russian and is available to most physicists in a single inadequate abstract. I am indebted to Dr. D. E. Olshevsky for its translation. In his second paper he reports the interesting fact that the change in resistance for magnetization is greater after preliminary magnetization at right angles.

Cantone (Items 8, 9 and 10) was the first to obtain the now familiar "butterfly" loops in magneto-resistance. His elasto-resistance data did not disclose "lag" or "priming," but those of Ercolini (Item 19) show lag and Nobile (Item 28) found both effects in a single specimen for different ranges in tension.

The most interesting of the recent papers is that of Vilbig (Item 37). Though he seems not to be acquainted with the history of magneto-resistance he reports some curious variations in resistance for values of $H$ in the neighborhood of the coercive force. There appear from his data to be two distinguishable states of nickel in this region, in one of which (*stabile Zustand*) the resistance variations are reversible, in the other of which (*labile Zustand*) they are irreversible.

The most recent work on elasto-resistance (Items 36 and 38) suffers from a really astonishing paucity of both data and historical background.

## New Data

**First Series, 1920-1923.**

Late in 1920 Dr. H. D. Arnold[23] was struck by the fact that usual methods of measuring the electrical resistance of wires gave erratic results in the case of an alloy containing 77 percent nickel, 23 percent iron. He traced

[23] Director of Research, Bell Telephone Laboratories (in 1920, Engineering Department, Western Electric Company).

this variability to the unsuspectedly large effects of moderate tension and of stray magnetic fields—especially the magnetic field of the earth—and showed that for this particular composition of what was later called permalloy, tension and magnetization were roughly equivalent in their effects upon resistance. He expressed this equivalence by the equation

$$\Delta R = f(H + kT)$$

where $f(x)$ is a function of $x$ which has a maximum value within easily attainable limits of $H$ and $T$, and $k$ is a constant roughly equal to 0.0035 if $H$ is in gauss and $T$ in kg/mm$^2$.

In 1922[24] I examined the data upon which this conclusion was based and decided that the equivalence of $H$ and $T$ was not so perfect as Arnold's equation suggests. For low values of $H$ and $T$ the best value of $k$ is considerably greater than 0.0035, meaning that the $\Delta R$—*vs.*—$H$ curve rises more steeply from the origin than does the $\Delta R$—*vs.*—$T$ curve if they are so plotted as to agree best in their middle ranges.

During the summer of 1923 my assistant, Mr. P. P. Cioffi, who had also assisted in the experiments of 1920, measured for me the changes in resistance under tension, magnetization, and combinations of tension and magnetization, in the series of permalloys of special purity used by Dr. O. E. Buckley and myself in a study of changes in magnetization curves and hysteresis loops due to tension.[25] Other permalloys, of commercial purity, were also available and were measured at this time. The methods of supporting and stretching the wires, and of measuring changes in magnetizing field and magnetization have been fully described.[26] The additional apparatus needed for resistance measurements consisted of current connections at the ends of the wire under test, two fine wires welded to the specimen in the region of uniform magnetization to serve as potential taps, and a potentiometer for measuring the difference of potential between these taps under the various conditions. In these experiments there was no provision for protecting the specimen from heating by the magnetizing solenoid, so that $H$ could not conveniently be made much more than 6 gauss.

The results of these tests confirmed the existence of a transition in properties at a composition in the neighborhood of 81 percent nickel. A brief note dealing with a single composition (78.5 percent nickel) was presented at a meeting of the Physical Society late in 1923.[27] One of the drawings then exhibited was published about three years later,[28] together with a statement regarding the signs of magneto-resistance and of elasto-resistance in tension on both sides of 81 percent nickel. The method of reducing the

[24] At the Bell Telephone Laboratories.

[25] O. E. Buckley, L. W. McKeehan, Phys. Rev. [2] **26,** 261–273 (1925). These same wires were also used in later work on magnetostriction: L. W. McKeehan and P. P. Cioffi, Phys. Rev. [2] **28,** 146–157 (1926).

[26] P. P. Cioffi, J. Opt. Soc. and Rev. Sci. Inst. **9,** 53–60 (1924).

[27] H. D. Arnold, L. W. McKeehan, Phys. Rev. [2] **23,** 114 (1924).

[28] L. W. McKeehan, J. Franklin Inst. **202,** 737–773 (1926); especially pp. 762–763.

observations at the time they were made—by slide-rule—obscured the fact that they are self-consistent to a high degree and, in the aggregate, present interesting information regarding magneto- and elasto-resistance in general. The whole set of data has recently been reduced by methods which preserve the precision really attained,[29] and a considerable number of representative curves are here presented for the first time.

Fig. 7 shows the effect of tension alone for a total of 27 annealed[30] specimens of (about) one millimeter wire in the range from 65 to 90 percent nickel. Lines which terminate at relatively small values of tension belong to specimens—all of the purer series—which suffered from crystalline brittleness.

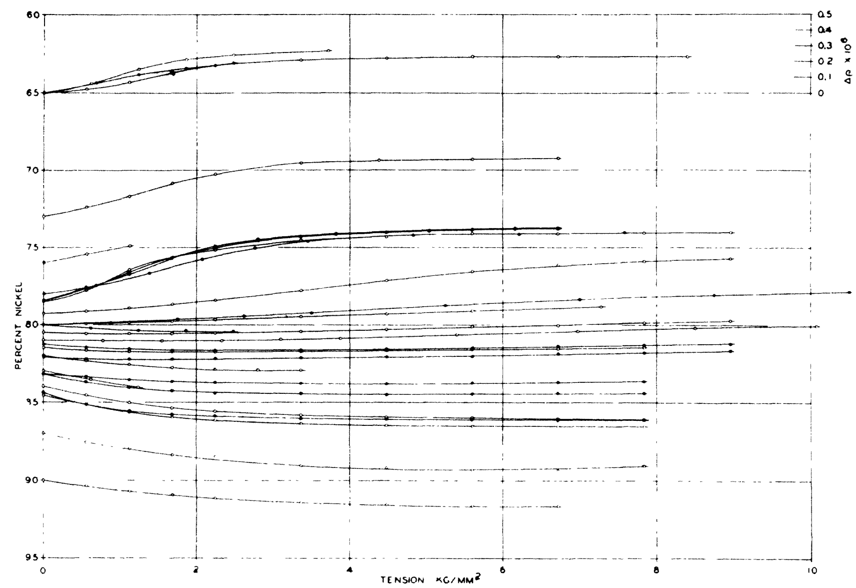


Fig. 7. Elasto-resistance in permalloy under tension—1923.

It will be noticed that these short curves are only a little steeper and straighter than those for neighboring alloys of more normal mechanical soundness.

Fig. 8 shows how the application of a magnetic field has different effects under different steady tensions, including zero tension in each case.

It will be noticed that I have departed from precedent in plotting the change in resistivity,[31] $\Delta\rho$, rather than the proportional change in resistance, $\Delta R/R$. This departure seemed advisable because the resistance, $R$, for specimens of equal dimensions, and with it the resistivity, $\rho$, and the ratios $\Delta R/R$ and $\Delta\rho/\rho$ vary widely with nickel content—by a factor of 6 within

[29] I am indebted to my former colleagues at the Bell Telephone Laboratories for the loan of notebooks containing the original records of these experiments.

[30] Held at 960° C in vacuum for one hour and cooled to room temperature in about an hour.

[31] The resistivity $\rho$ has *not* been corrected for changes in dimensions of the specimens under tension. These changes were not measured and in comparison with such large changes as here occur the correction due to these elastic deformations is safely negligible.

the range covered—and because, for one and the same nickel content $R$, $\rho$, $\Delta R/R$ and $\Delta\rho/\rho$ are correspondingly sensitive to small differences in purity, in mechanical soundness and in thermal state or history. As the specimens were not all of the same diameter $\Delta R$ was an unsuitable index of the effect under investigation and $\Delta\rho$ was the only quantity fairly characteristic of nickel content alone. It can be argued that the effect of tension or of a magnetic field is to produce, increase or diminish an additive resistivity of the same kind as that due to alloying, *i.e.* independent of the change in resistivity due to change in temperature and, presumably, equally independent of additive resistivities due to structural imperfections and the

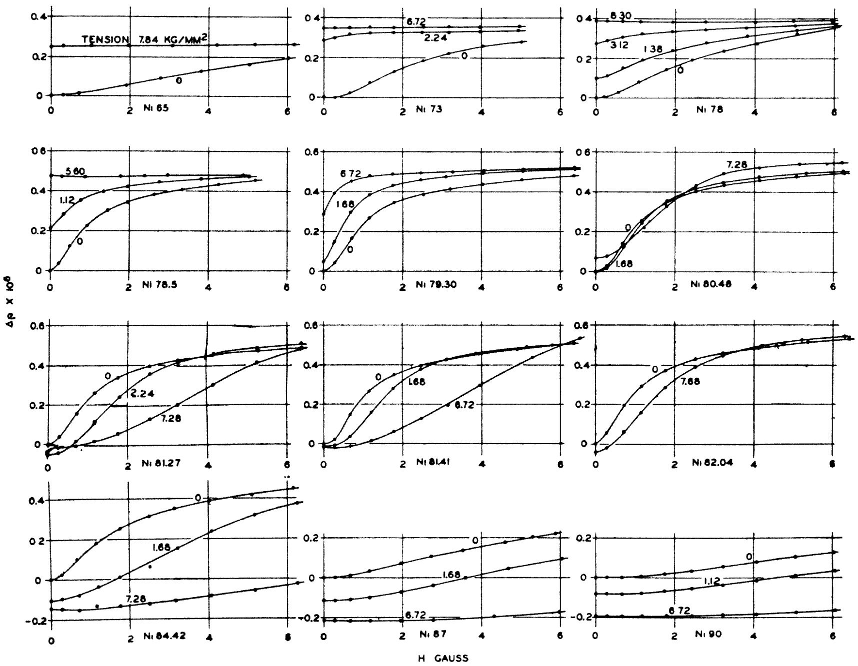


Fig. 8. Effect of tension on longitudinal magneto-resistance in permalloy—1923.

like. In case it is desired to convert any value of $\Delta\rho$ into the proportional change $\Delta\rho/\rho$ to be expected in pure, sound, metal the values of $\rho$ given by Sizoo and Zwikker[32] are probably the best available.

The purer series of alloys were made in such small lots that they could not easily be analysed, and for the same reason the probable error in their compositions is large. Some of the discrepancies in Fig. 7 are probably due to deviations of actual from intended nickel-iron ratio in members of this series, especially at about 80 percent nickel where a small change in composition changes the sign of elasto-resistance. Wherever, in Fig. 8, the

[32] G. J. Sizoo and C. Zwikker, Zeits. f. Metallkde. **21,** 125–126 (1929). These authors are probably wrong in ascribing every peculiarity of the $\rho$-*vs.*-nickel content curve to the existence of a definite nickel-iron compound.

nickel content is given to hundredths of a percent this datum is the result of one or more analyses on wire drawn from the same casting. It cannot be expected, however, that the nickel content of any particular specimen is known with a smaller probable error than $\pm 0.2$ percent.

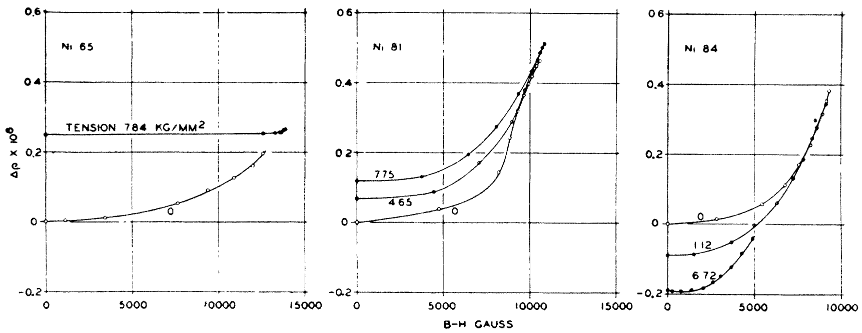


Fig. 9. Effect of tension on longitudinal magneto-resistance in permalloy, as a function of magnetization—1923.

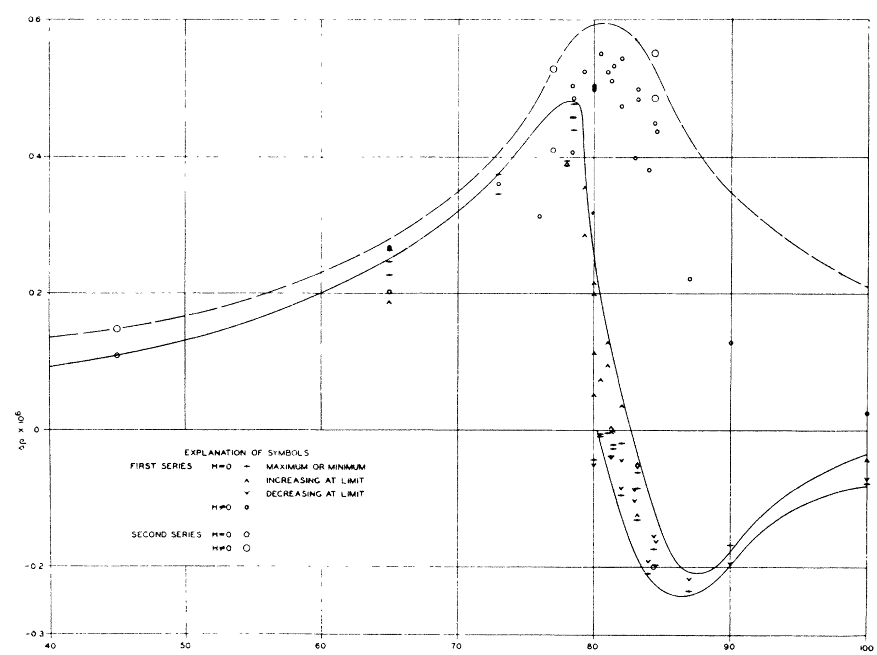


Fig. 10. Magneto-resistance and elasto-resistance in permalloy, as a function of nickel content.

The magnetization curves for the alloys particularly studied by Dr. Buckley and myself[25] were also obtained at about the same time as the resistivities and have been used to obtain—in Fig. 9—the relation between $\Delta\rho$ and $B-H$ in the cases of three compositions. These curves are not so simple as to suggest that much would be gained if it were possible to obtain like curves for all of the specimens. One objection to such an attempt is that measurements at a single value of $H$ can easily be repeated with accuracy by using high-capacity storage batteries and resistance boxes, whereas a value of $B-H$ is hard to duplicate.

Fig. 10 presents many of the results displayed in Figs. 7 and 8, and additional results of the same sort from experiments for which detailed curves are not here reproduced. It shows that for permalloys with less than about 79 percent nickel the effect of tension is of the same sign as that of magnetization, and that the greatest positive value of $\Delta\rho$ due to tension within the elastic limit in this range of composition may be nearly as great as that due to magnetization alone or to any combination of pull and magnetic field. Between 79 and 100 percent nickel tension within a safe limit is incompetent to increase the resistivity as much as magnetization can, so that the full line which runs close beneath the broken line for low nickel content here drops far beneath it. It is worthy of remark, however, that the course of the curves at the safe limit in tension makes it not unlikely that if the necessary tensile stress could be applied without damage to the specimen the final resistivity in tension might again be nearly as high as that produced by magnetization.

Beyond a somewhat ill-defined point which has been chosen in Fig. 10 at 80.5 percent nickel, the initial effect of tension is to diminish $\rho$ so that $\rho$ passes through a minimum within the safe range of loading. Close to or at the same critical composition the magneto-resistance effect passes through a well-marked maximum.

The data of 1923 do not permit any very definite statements regarding the effects of magnetization in permalloys with more than about 83 percent nickel, because $H$ could not be pushed high enough to obtain the saturation value of $\Delta\rho$. The results of previous investigators on pure or nearly pure nickel have been used to establish the right-hand end of the broken line in Fig. 10 and the gap has been filled in on the supposition that the magneto-resistance effect at saturation is roughly symmetrical about the maximum near 81 percent nickel.

**Series of 1929-1930.**

An additional series of experiments was undertaken in this laboratory about a year ago with the idea of extending the range in $H$ and to clear up a difficulty which can best be understood by reference to Fig. 8. While it is abundantly clear that the principal effect of increasing $H$ from zero is to increase $\rho$, there are numerous $\Delta\rho$—*vs.*—$H$ curves which first pass through a shallow minimum.[33]

Since the procedure in 1923 included a preliminary demagnetization[34] it seemed impossible to explain this minimum as due to the suppression of an initial magnetization in a direction opposite to that in which $H$ was increased during the experiment itself. It appeared possible that the process

[33] The reality of these minima was not apparent until the data had been reanalysed as explained above.

[34] By decreasing to zero amplitude an alternating magnetic field in the presence of a constant field adjusted to compensate the vertical component of the earth's magnetic field.

of demagnetizing might have heated the specimen, the initial drop in $\rho$ then being attributable to cooling. Both purposes required better control of the temperature of the specimen and advantage was accordingly taken of some improvements in technique devised for the even more exacting requirements met in studying magnetostriction.[35]

The new magnetizing coil was wound on a double-walled glass jacket inside which were the specimen, potential leads and search coil. There was now—as there had not been in the magnetostriction studies—a source of heat inside the jacket, since a current had to be maintained in the specimen to permit the measurement of its resistance. It was therefore necessary to pass a heat-absorbent material through the jacket rather than to evacuate and silver it. In order to prevent the condensation of atmospheric water vapor on parts within the jacket, and to make it feasible to leave the lower end open so as to constrain the loaded end of the specimen to the least possible degree, the tap-water used as a coolant was circulated through the jacket at a temperature several degrees above that of the room. Most of the heat necessary to maintain this excess temperature was furnished by a manually controlled gas heater. Final adjustment, usually to 26°C, was effected by a 400-watt electric heater controlled by a mercury-under-hydrogen switch operated by a thermostat of the Stirlen type[36] between the electric heater and the jacket. With a convenient flow of water it was found by direct experiment that the temperature of a representative specimen did not vary by as much as 0.01°C during normal operation. For a magnetizing current corresponding to $H=50$ the rise in temperature of the specimen produced a change in resistance negligible in comparison with those to be measured. The barometric height affects the equilibrium temperature of the cooling water, and other things, particularly the room temperature, make slight differences in the temperature of a specimen for the same water temperature. For these reasons sets of data taken at intervals of a day or more frequently yielded slightly different values of $\rho$ for what were meant to be identical conditions. Such differences are believed, for reasons already mentioned, to have little or no effect upon the values of $\Delta\rho$, provided a standard magnetic and mechanical condition can be reestablished at intervals to furnish a bench-mark.

The three alloys chosen for study contained about 45, 77 and 85 percent nickel, and were furnished by the Bell Telephone Laboratories in the form of 40-mil (about one millimeter) wires. Analysis of one of these and analyses of materials of similar manufacture indicate the presence of impurities about as follows:

| | | | |
|---|---|---|---|
| Co | 0.2 percent | Si | 0.01 |
| Mn | 0.2 | C | 0.01 |
| Al | 0.05 | S | 0.005 |
| Cu | 0.05 | P | trace |

[35] *loc. cit.*[25] second reference.

[36] A mercury column balanced by the vapor pressure of a suitable mixture of ethanol and ethyl ether in a bulb completely submerged in a small reservoir.

Suitable lengths of the hard-drawn wires were straightened and then were heated, while hanging vertically in hydrogen at atmospheric pressure, to about 1000° for one hour by passing an alternating electric current through them. Cooling was rapid. Care was taken to avoid bending or twisting the prepared specimens, even elastically, and the results obtained with good specimens did not depend upon the order in which experiments were performed.[37]

Figs. 11 to 13 inclusive present resistivity changes as a function of $H$ for loops repeatedly traversed between equal positive and negative values of $H(\pm 23.4$ gauss), under various steady tensions well within the elastic limit. In 45- and 77-nickel permalloy the magneto-resistance effect is

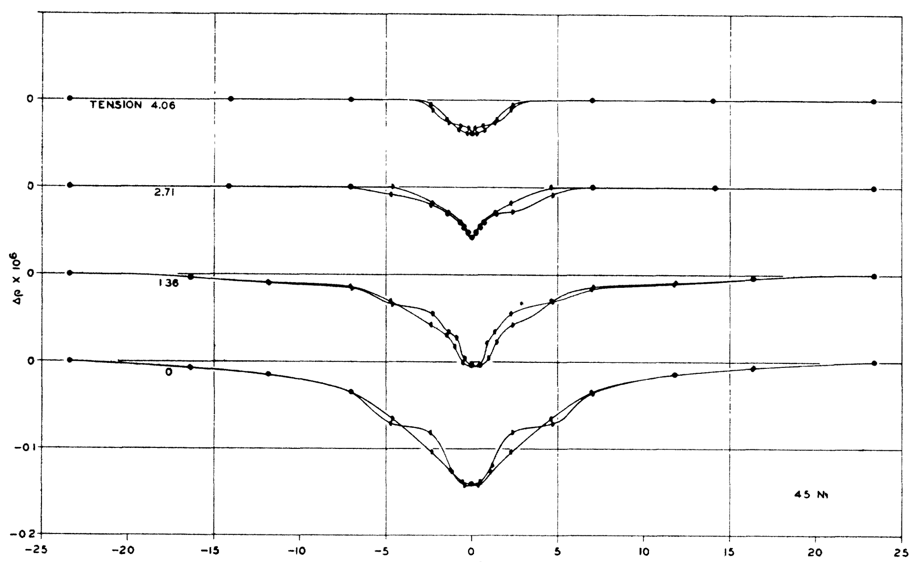


Fig. 11. Effect of tension on longitudinal magneto-resistance in permalloy with 45 percent nickel. Major loops.

thoroughly saturated at the peak value of $H$ so that this condition of maximum resistivity was chosen as standard. With this convention $\Delta\rho$ is negative and passes through its maximum negative value near $H=0$. In 85 permalloy (84.41 by analysis) the effect is hardly saturated by $H=23.4$ even for zero tension. All values of $\Delta\rho$ were therefore obtained with respect to the highest value of $\rho$ in the experiment under zero tension, and the difference in level with difference in tension in Fig. 13 is not as significant as in Figs. 11 and 12.

The method of taking observations, in which corresponding points for $+H$ on the descending branch and for $-H$ on the ascending branch are taken in quick succession, tends to make the errors symmetrical, since accidental causes more often than not produce like errors in consecutive

[37] The less consistent behavior of certain specimens is described later.

measurements of nearly equal values of $\rho$. This is very evident in Figs. 11 and 13. In Fig. 12, however, the curves are noticeably asymmetric. Still more asymmetric results were obtained in certain preliminary experiments on other specimens of 77 and 85 percent permalloy. The search for the cause of this asymmetry led to clearing up one of the questions at issue and must therefore be described in some detail.

In the preliminary experiments the $\Delta\rho$—*vs.*—$H$ curves were analogous rather to normal magnetization curves than to hysteresis loops. That is, $H_{\max}$ was repeatedly increased, $\rho$ being measured only for $+H_{\max}$ and $-H_{\max}$

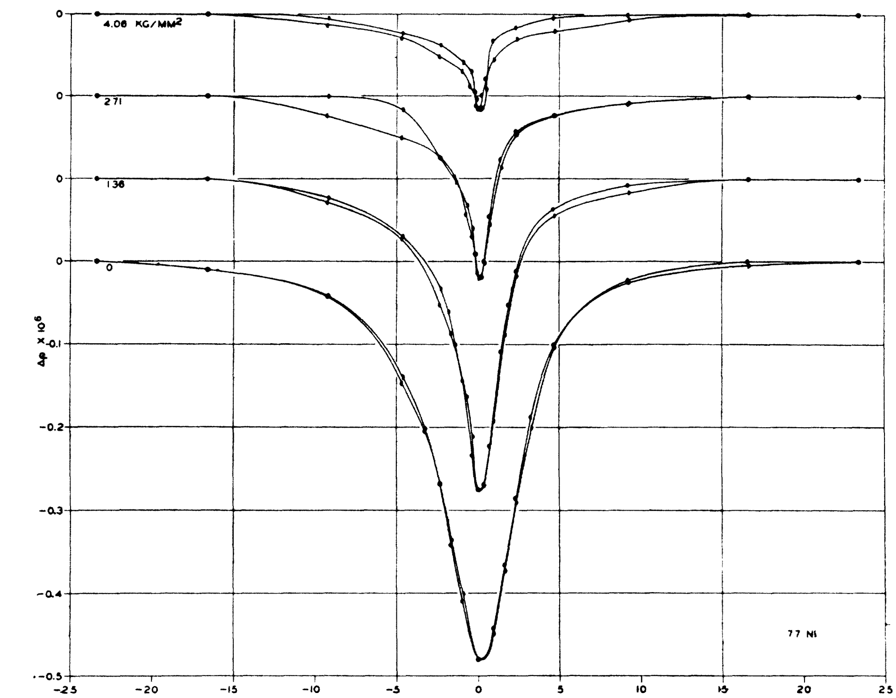


Fig. 12. Effect of tension on longitudinal magneto-resistance in permalloy with 77 percent nickel. Major loops.

at each step, so that the curve obtained was the locus of the tips of loops like those given in Figs. 11 to 13 for a particular value of $H_{\max}$. Fig. 14 gives part of the results obtained in this way for a particular specimen of 77 percent permalloy.[38] The curves are lettered to distinguish the order in which they were obtained, and black dots mark the starting points the centers of the ranges in $H$. The maximum applied field in these experiments—70 gauss—largely exceeds the limits of the figure. The value of $\rho$ for great

[38] The points upon which these curves depend have been omitted from Fig. 14 in the interest of simplicity. There are for each curve more than 60 measured values of $\Delta\rho$ with the range shown.

applied fields is the bench-mark for $\Delta\rho$ in each case. It will be noticed that $\rho$ reaches its limiting value within the limits of the figure on only two curves, *viz.* on the negative side of curve $D$, and on the positive side of curve $G$.

The very striking thing about Fig. 14 is that applying $H$ in one direction from the starting point decreases $\rho$ just as applying $H$ in one direction in the experiments of 1923 (see Fig. 8) sometimes decreased $\rho$. But now that *both* signs of applied field are used the smooth course of the $\Delta\rho$—*vs.*—$H$ curves through their starting points makes it evident that the initial states are not of any particular significance in respect to magneto-resistance.

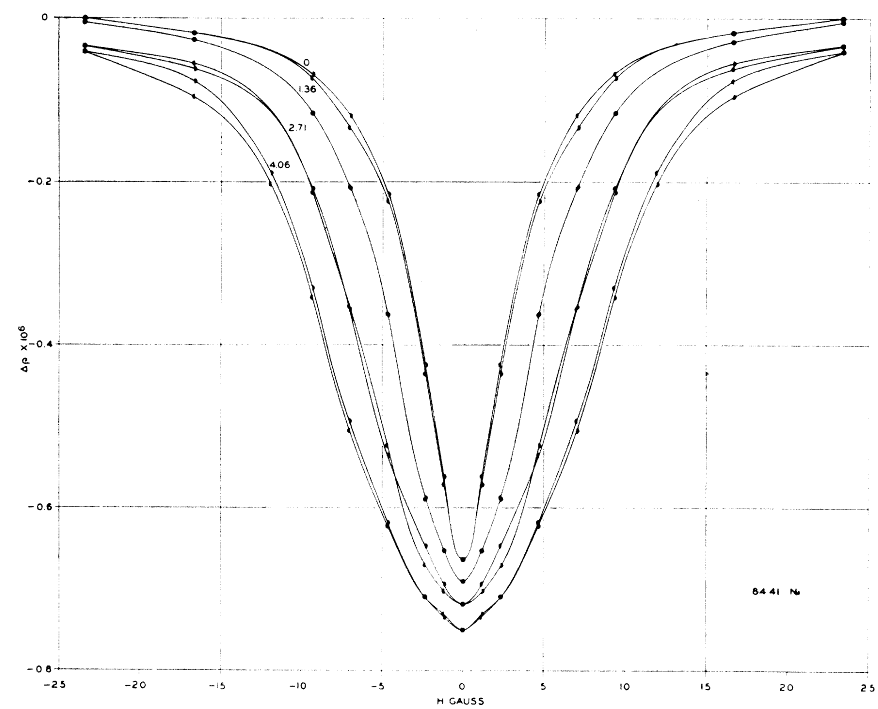


Fig. 13. Effect of tension on longitudinal magneto-resistance in permalloy with 85 percent nickel. Major loops.

An attempt had, of course, been made in every case to select a significant initial state, that of complete demagnetization in zero applied field. The process employed for this selection is one of those described in an earlier paper.[39] In it the specimen is carried repeatedly around a hysteresis loop of suitable range in $H$. It is then observed whether the changes in $B$ corresponding to equal steps in $H$ from the two tips of the loop are or are not equal. If they are equal the loop is symmetrical and its center is at $H=0$. If they are not equal the stray fields producing the asymmetry of the loop must be compensated before a demagnetizing process can be really effective.

[39] L. W. McKeehan, P. P. Cioffi, J. Opt. Soc. Amer. and Rev. Sci. Instr. **9**, 479–485 (1924).

In the experiments here under discussion the specimen to be tested had been used in the manner just described in adjusting the magnetic field applied to compensate that of the earth.[40] It had already been observed with some alarm that the compensating field so fixed varied much too widely. The obvious explanation was that the particular specimen in use did not follow symmetrical hysteresis loops in zero field. When the loops were forced to pass through four symmetrically disposed points—the tips and the two test

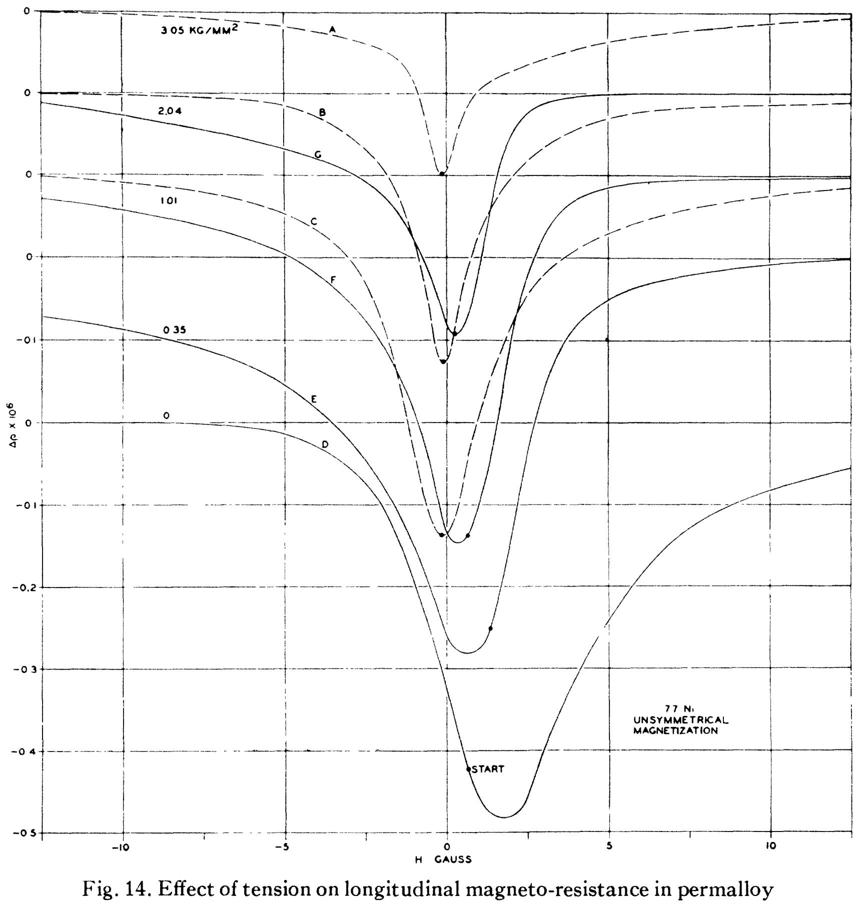


Fig. 14. Effect of tension on longitudinal magneto-resistance in permalloy with 77percent nickel—unsymmetrical magnetization.

points—the middle did not therefore lie at $H=0$ and when "demagnetized" at this fictitious origin for $H$ the specimen was left partly magnetized. As soon as this was realized a specimen known to give hysteresis loops symmetrical about $H=0$ was substituted for the suspect specimen and the true earth's compensating field thus measured. The results of this auxiliary experiment have been used in fixing the abscissas of the starting points in Fig. 14.

[40] The magnetizing solenoid carries a separate winding for this purpose. *loc. cit.*[26]

The question still remaining was why the specimen followed asymmetrical loops and how their asymmetry could change as profoundly as it evidently had between the experiments recorded in curves *C* and *D* of Fig. 14. Trial of several specimens prepared in the same way showed that asymmetry was more likely to appear in specimens which were slightly bent or otherwise visibly damaged than in those which passed every visual test. It has long been known[41] that the passage of an electric current through an apparently well-annealed wire will develop in it a magnetic asymmetry that is relatively persistent but that can be altered by reversing the direction of the current, by mechanical twisting, by vibration and the like. The reason for this is

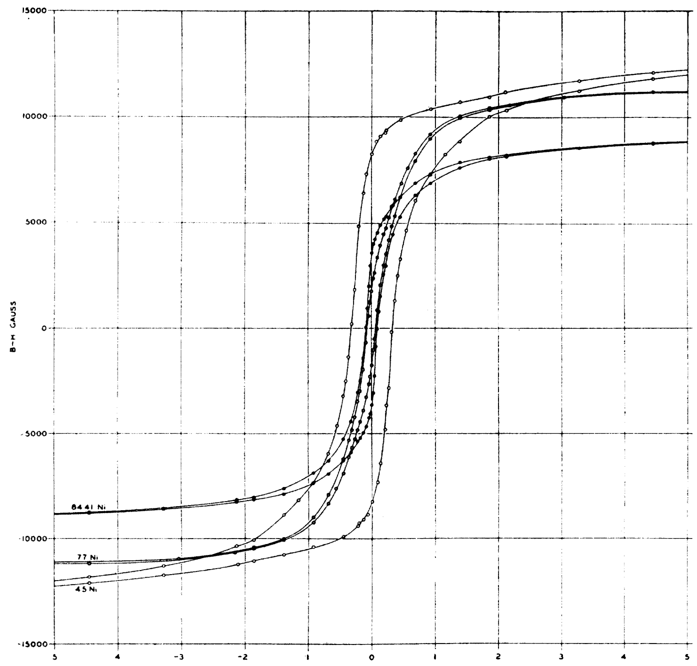


Fig. 15. Hysteresis loops for permalloy specimens of Figures 11, 12 and 13.

to be looked for in the mechanical history of the particular piece, especially in twisting and untwisting operations. In the wires here used, made in small lots and with much handling, it is not at all surprizing that specimens from the same lot should show local differences in subliminal twist in the finally annealed condition. Neither is it surprizing that this mere ghost of a dead twist might have been altered by accident in the interval between the taking of data for curves *C* and *D*.

The specimens used in getting Figs. 11 to 13 give symmetrical hysteresis loops, as is shown, for zero tension, in Fig. 15. This confirms the conclusion as to their relative excellence derived from the magneto-resistance tests

[41] D. E. Hughes, Proc. Roy. Soc. **32,** 25–29 (1881).

already described, in which the earth's compensating field was correctly adjusted. Besides the wide loops of Figs. 11 to 13, and some still wider, a great many narrower loops have been traced. A few of these are presented in Fig. 16.

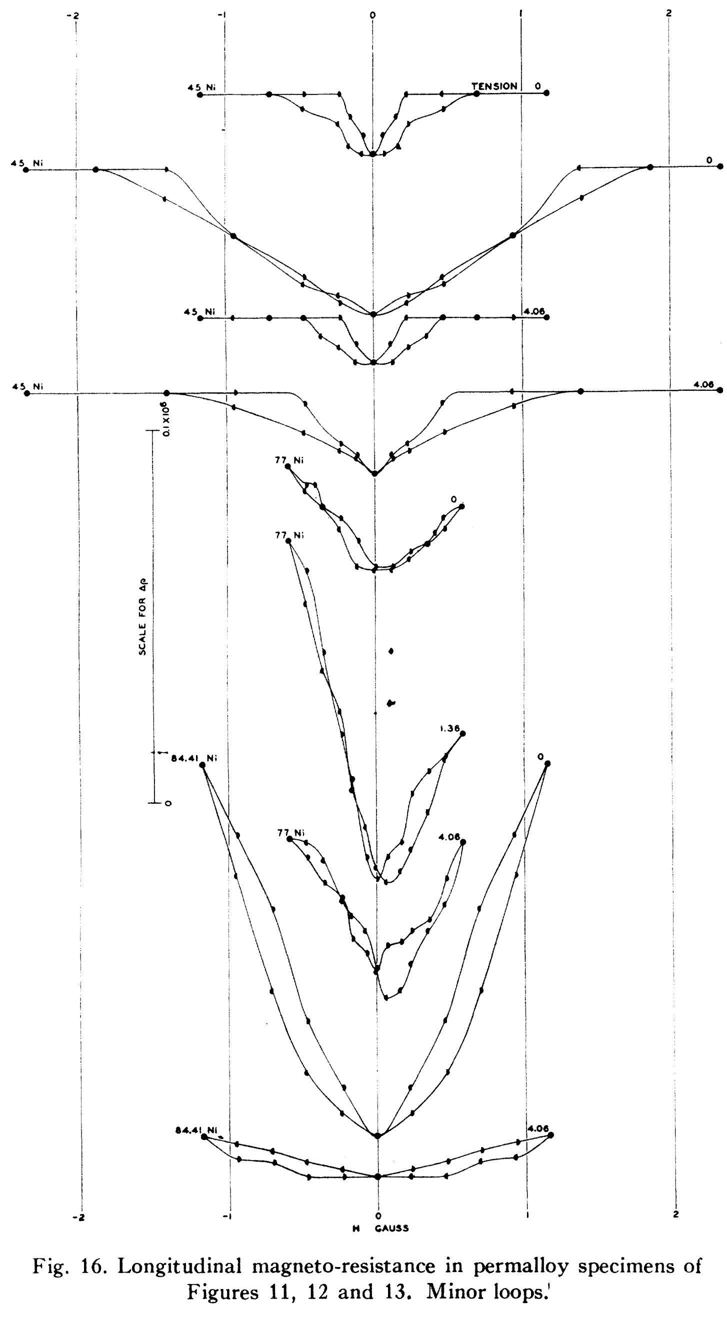


Fig. 16. Longitudinal magneto-resistance in permalloy specimens of Figures 11, 12 and 13. Minor loops.

In all the work so far described in this section the changes in magnetization, corresponding to each change in $H$ were followed ballistically, so that $\Delta\rho$ has also been obtained as a function of the magnetization $(B-H)$. Figs. 17 and 18 show some characteristic curves of this sort. As in the first series,

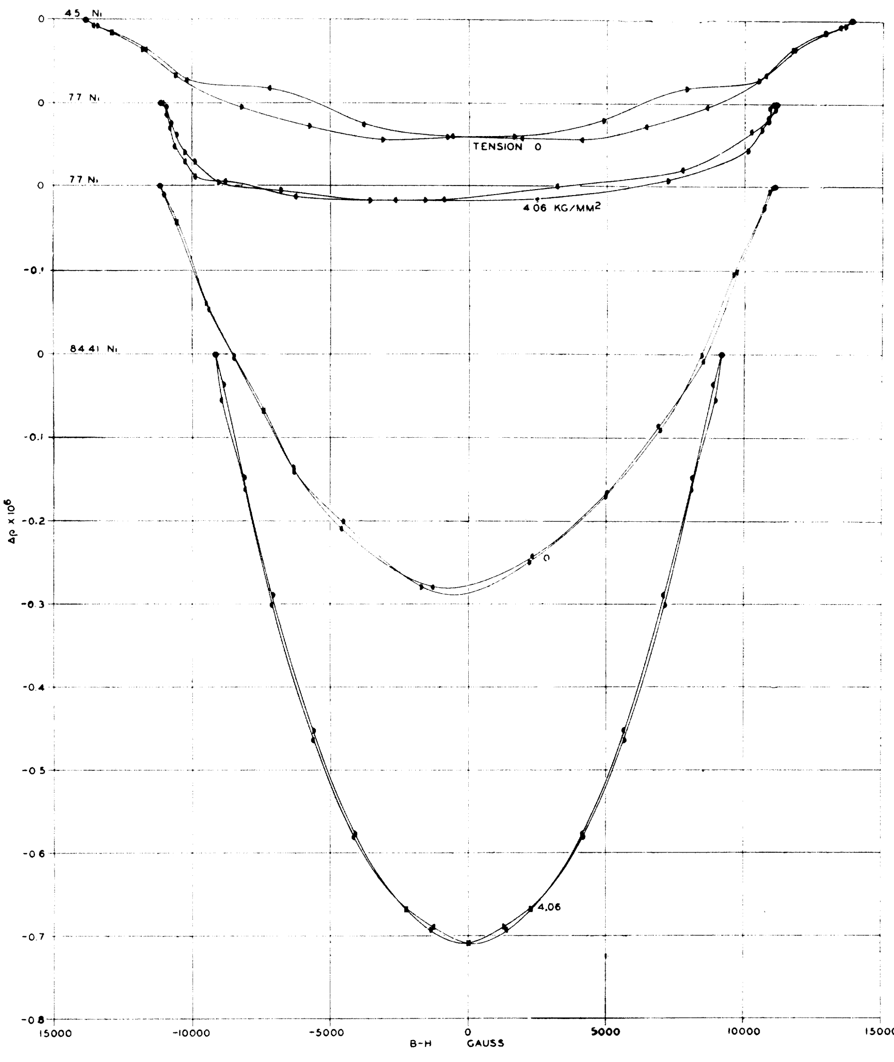


Fig. 17. Longitudinal magneto-resistance as a function of magnetization for permalloy specimens of Figures 11, 12 and 13. Major loops.

however, there is little or no advantage in thus presenting the results, and there is some loss in considering the relations between two dependent variables rather than between one dependent and one independent.

The bizarre appearance of Fig. 11 made it seem possible that the magnetization of the specimen had been notably discontinuous. The magnetic meas-

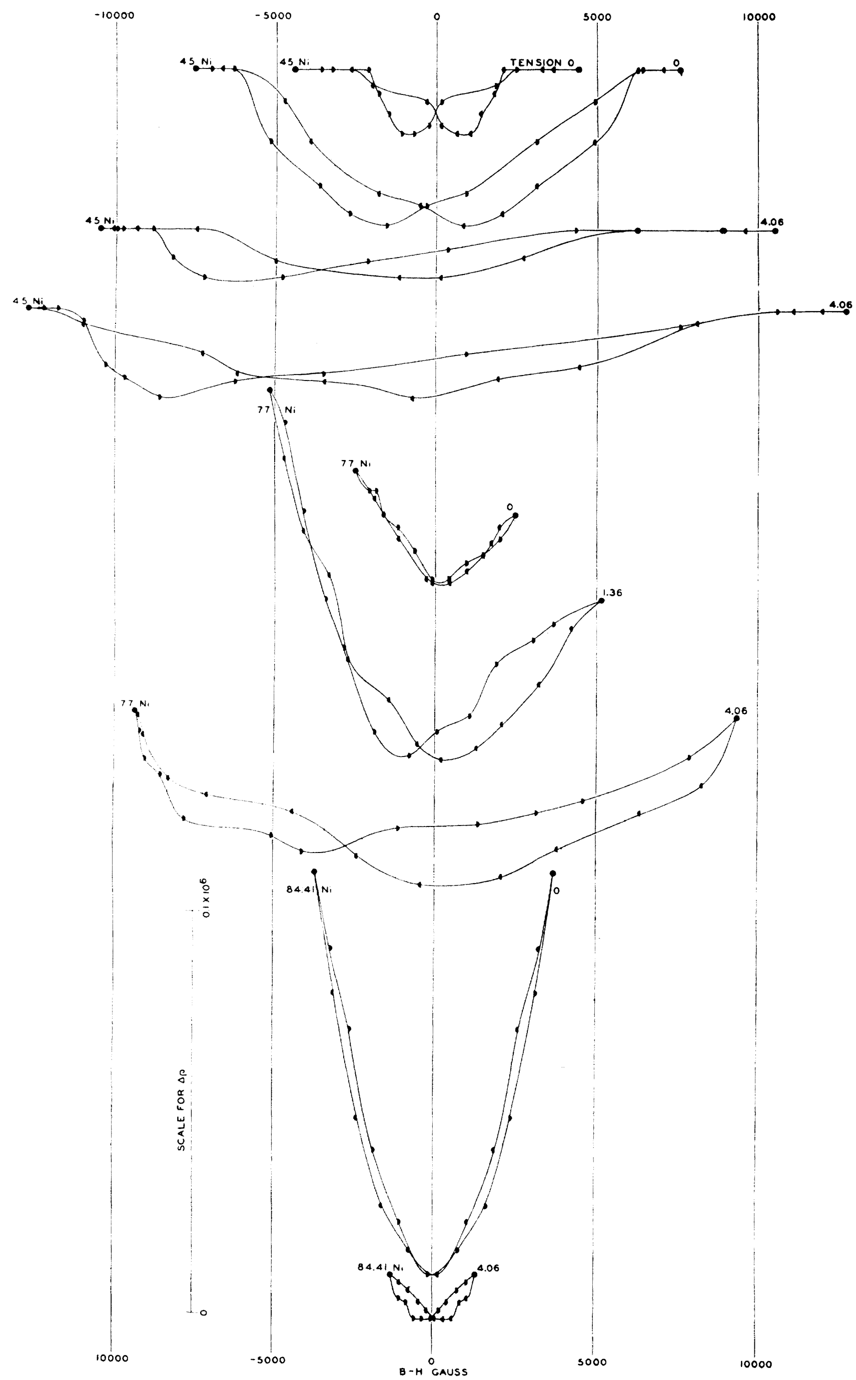


Fig. 18. Longitudinal magneto-resistance in permalloy specimens of Figures 11, 12 and 13, as a function of magnetization. Minor loops.

urements shown in Fig. 15 disposed of this idea and it seemed advisable to measure the variations in $\rho$ during a loop traversed as smoothly and continuously as possible. Since the jerkiness of the previous traverses[42] was largely due to the inclusion of ballistic measurements of magnetization changes this feature was dropped for the special experiment. A potential divider was so constructed of slide-wire resistances that the current through the magnetizing coil could be varied continuously in either direction between about $+1$ amp. and $-1$ amp. This current was measured by a micro-ammeter across shunts of such low resistance that the transfer of the micro-ammeter from one shunt to another in changing the range of this make-shift ammeter did not sensibly disturb the current being measured. The resistivity was now measured for consecutive points around a loop about as wide as those in Fig. 11 and under no tension. The results in $\rho$ are plotted in Fig. 19 which shows a highly irregular loop with the three main crossings seen in Fig. 11 and a pair of more doubtful crossings on one side only. It must be concluded that the principal irregularities are not due to the step-by-step character of the earlier tests on this specimen.[43]

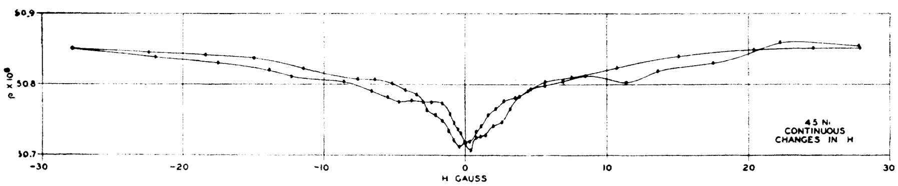


Fig. 19. Longitudinal magneto-resistance in permalloy with 45 percent nickel, for continuous variation of magnetizing current. Major loop.

Points have been placed on Fig. 10 to show that the new data support and extend the old. For 45 and 77 percent nickel the correspondence is good. For 85 percent nickel arbitrary correction terms ($-0.112$ and $-0.079$ in $\Delta\rho$) have been applied to lower the points plotted for this alloy until the points for tension alone agree with the earlier curve. Such a correction would be theoretically justified if the annealed specimen had its structure modified in the way that low tensions favor. It would probably be more logical, however, to suppose that all three alloys suffered in the same way but to a smaller extent. This would involve raising all the plotted points that have been derived from the second series of experiments by about 0.05 in $\Delta\rho$. The trend of the new points would still agree with that of the old, but the magneto-resistance limit would have to be raised higher than it has been drawn.

## Discussion of Results

In this discussion I propose to regard the specimens as assemblies of atoms, for the most part associated with the points of a space-lattice, and, as far as may be, to interpret the findings in terms of atomic properties and

[42] *loc. cit.*,[26] control of magnetizing current by a battery of knife switches.

[43] There was an interval of seven months between the tests here compared.

inter-atomic relations. This mechanistic method has pictorial advantages and probably will serve to describe the phenomena as well or better than the more up-to-date statistical method.

The difference, emphasized in the introduction, between magneto-resistance in ferromagnetics and in other metals, suggests that the disturbance of electric conduction producible by magnetic fields has, in ferromagnetics, already proceeded far in zero *applied* field. Let us assume, therefore, that the most important part of each atomic domain in a ferromagnetic metal is occupied by a self-maintained magnetic field so intense that in comparison with it the most intense fields yet used in the study of magneto-resistance are nearly negligible.[44] Applied fields can therefore only affect conduction in ferromagnetics by aligning these atomic fields and by the relatively trivial changes in inter-atomic regions which must result from such alignment.

Kapitza[2] has supposed that conduction is affected almost as much by random local fields and by uniform fields of the same average scalar magnitude. The present suggestion is that this small difference in effect is the whole magneto-resistance effect in ferromagnetics.

The principal result of the experiments on permalloy is (*cf.* Fig. 10) that the maximum effect of tension in a particular class of alloys is nearly equivalent to the maximum effect of magnetization, and that both agents together are no more effective than magnetization alone. This means that the atomic fields we have postulated can be aligned by tension as well, or nearly as well, as by magnetization. If the alignment effected by tension is as nearly perfect as that effected by an applied magnetic field, the slightly smaller change in resistivity for tension is to be explained as due to the lower average magnitude of the interatomic field between oppositely directed atomic magnets. Otherwise we must neglect the effect of regions remote from any magnetic element, and explain the lower efficacy of tension by supposing, probably in accordance with fact, that the mechanical stress within the stretched specimen is not as homogeneous as the magnetic field due to current in an enclosing solenoid. It is obvious that mechanical stresses can only affect the orientation of atoms with less than spherical symmetry, and that the asymmetry must be spatially related to the magnetic axis in each atom.

This line of reasoning applies also to cases where the initial effect of tension and the effect of longitudinal magnetization are opposite in sign. Here we have only to assume that moderate tension renders the arrangement of atomic magnetic axes less nearly parallel and more nearly transverse to the direction of current.

The plausibility of these assumptions is much greater in view of the

[44] It may be noted that a magnetic dipole having the magnetic moment associated with each atom of nickel at saturation produced a field in excess of $3\times10^5$ gauss throughout less than one percent of the atomic volume, so that a magnetic element much less compact than a dipole is indicated. The intense magnetic fields here dealt with should not be confused with the "molecular field" of Weiss which controls the interaction of atoms and must be located principally in interatomic regions.

measurements on magnetostriction,[35] which show that tension decreases the magnetostrictive expansion in permalloys with less than about 81 percent nickel, and increases the magnetostrictive contraction in those with more than this nickel content. There is, to be sure, an element of extrapolation in establishing a quantitative relation between magnetostriction and elasto-resistance effects. The maximum magnetostrictive strain is much less than the strain necessary to saturate the elasto-resistance effect. (There is as yet no proof that the elastic and magnetic strains are exactly similar.) Secondary effects are therefore to be expected in tension rather than in magnetization. The change in sign of $\partial\rho/\partial T$, at an attainable value of $T$, in nickel and nickel-rich alloys is such a secondary effect that may well repay further study.

A striking feature of Fig. 10 is the maximum in $\Delta\rho$ for magnetization at about the critical composition dividing alloys which expand when magnetized from those which contract. Striking as this maximum is, it may be unimportant in the theory of these phenomena. The current maintained in the wires for resistance measurement produces a transverse magnetic field which, near the surface of the wire, is enough, by itself, to maintain approximate magnetic saturation in the more easily magnetizable permalloys. What is measured, then, is the whole change in resistance from a condition of transverse magnetization to one of longitudinal alignment. The fact that the peak value is about twice that for pure nickel (where the transverse magnetization is certainly slight) lends support to this hypothesis, since the transverse effect, when correctly measured in ferromagnetics is always of about the same magnitude as the longitudinal effect, and opposite in sign.[45]

The irregularity of many curves and the confusion of points near 81 percent nickel in Fig. 10 are not regarded as being especially significant. It seems more reasonable to suppose that local variations in composition are chiefly responsible. If the resistivity varies from point to point the distribution of current over the cross-section also varies from point to point and the average resistivity as measured is not a simple space-average but a more sensitive function of the independent variables. The 45 percent alloy lies near a resistivity maximum and the critical region is one where resistivity changes rapidly with composition. Changes in flux distribution over the cross-section, involving changes in resistivity, provide a secondary source of non-uniformity of current.

More important than these casual irregularities is the definite evidence, most strikingly presented in Figs. 9 and 17, that $\Delta\rho$ is not, for these materials,

[45] Considerations of the same sort support the negative correction used in placing points on Fig. 10 for 84.41 Ni (Second Series). In annealing a vertically hung wire of this compositon both the heating current and the weight of the specimen conspire to establish transverse settings of the atomic axes, and thus to decrease the subsequent decrease of $\rho$ under tension, to increase the increase of $\rho$ for magnetization. For the other alloys treated in the same way the heating current and the weight of the specimen act in opposite senses upon the arrangement of atomic axes. The wires of the first series were annealed horizontal in a tube furnace, so that no such correction was called for in plotting the results.

any simple function of the magnetization. This is no surprize, because it is implied by the fact, already noted, that magnetization of certain stretched alloys does not change their resistance. Such magnetization must be regarded as due to the reversal in direction of atomic magnets originally anti-parallel to the applied magnetic field. It will be natural, therefore, to expect that any changes in magnetization due to reversals will be without effect upon electric conduction.

In well-annealed strain-free metal changes in magnetization involve at each stage both reversals of atomic magnets and changes of another sort which may conveniently be pictured as rotations of the elementary magnets through less than 180°. It has been suggested in an earlier paper[46] that reversals involve no hysteresis, as they have no effect upon magnetostriction. The smooth curvatures of the hysteresis loops plotted in Fig. 15 are therefore taken to indicate that partial rotations occur at all stages. Consistent with these ideas is the smooth and nearly parabolic course of $\Delta\rho$—*vs.*—$(B-H)$ curves under these conditions. As suitable stresses are applied, the separation of the two modes of magnetization becomes sharper, the reversals occurring within a narrower range of $H$ and accounting for a larger fraction of the whole change in magnetization. The hysteresis loops become more nearly rectangular,[47] hysteresis losses and magnetostriction decrease, and as the new data show, the central portions of $\Delta\rho$—*vs.*—$(B-H)$ curves become so flattened that they no longer suggest parabolas.[48]

Minor hysteresis loops always have some area, and in accordance with the ideas just presented, must therefore involve both reversals and partial rotations. It is consistent with our picture of the phenomenon, therefore, that there are sensible changes in $\rho$ in traversing loops wholly within the limits of the flat central portion of more extensive loops. Though the changes in magnetization might have been accounted for by reversals alone, all the experimental evidence is against this supposition.

There remains one paradoxical fact which gives further information about the mechanism of electric conduction. Though it is necessary to proceed well toward magnetic saturation before the magneto-resistance effect becomes important, the effect saturates sharply before magnetic saturation is attained. This must mean that the disorganizationof electric conduction is sensibly complete before exact parallelism of magnetic axes obtains. One or both of the following conclusions are reasonable.

In the first place we may argue that this experimental fact proves that many paths of electric conduction are oblique to the wire axis. The average velocity of electrons is, of course, still along this axis, but small deviations of magnetization from exact parallelism with the axis become unimportant in fixing the mean resistivity.

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

[47] *loc. cit.*[25] first reference.

[48] Actually the smoothest and most regular of these curves require $n>2$ in any assumed relation of the form $\Delta\rho=(\Delta\rho)_0+A\,|(B-H)^n|$.

In the second place we may argue that only when the adjacent atoms in a crystal are oriented in particular ways with respect to the line joining their centers, is conduction along that line unhindered, and that reversing either or both of these atoms leaves the favorable condition unaltered. If this be admitted it follows that as soon as the applied magnetic field reaches such a value that any favorable aspect of adjacent atoms is improbable, further increase of applied field, though it increases the probability of exact parallelism—magnetic saturation—can have no further effect upon conductivity.

A decision between these conclusions can be made by measuring the resistivity of monocrystalline specimens in directions inclined to the axis of magnetization.

The diversity of results presented in the review of previous work is now seen to be a natural consequence of the inter-play of magneto-resistance and elasto-resistance changes. Among the most puzzling of the early results were the cases reported by Williams[49] in which annealing diminished the saturation value of $\Delta R/R$ due to magnetization. We now explain this anomaly by the existence in his unannealed wires of a preferred orientation of atomic axes due to tension, and the return to a more nearly random distribution of magnetic axes in the process of annealing.

Part of the spread of values in the earlier literature must be due to abnormalities in resistivity. Low values of $\Delta R/R$ are particularly suspect, since the purest specimens would have the highest values of this quotient.

It will be noticed in Figs. 2, 3 and 4 that the magneto-resistance effect saturates sharply whatever its maximum magnitude, and that the initial slopes of the several curves vary widely. The latter fact points to the existence in the various specimens of widely different initial conditions. Even if the maximum resistance in each case had been chosen for reference the resulting curves could not be superposed. This suggests that in the state of maximum resistance different specimens have different distributions of internal stresses tending to disorganize the arrangement of atomic magnetic axes produced in magnetizing.

## Conclusion

The principal features of magneto-resistance and elasto-resistance in nickel and permalloy for longitudinal magnetization and tension have been presented and discussed. Previous results and the results of new experiments can be adequately explained in terms of atomic orientation provided: (1) each atom has a fixed magnetic moment and a magnetic axis definitely related to its mechanical asymmetry; (2) magnetization is effected by two processes, conveniently termed reversals and partial rotations of atomic magnets, the relative importance and sequence of which depend principally upon mechanical stresses; (3) electrical conduction is affected primarily by the atomic magnetic fields within single atoms, secondarily by the mutual

[49] Bibliography Item 16.

aspect of adjacent atoms, and little or not at all by applied magnetic fields of the order of a few thousand gauss.

Matters requiring further study are: (1) the change in sign of $\partial\rho/\partial T$ as tension passes a critical value in nickel and nickel-rich alloys, (2) the early saturation of the magneto-resistance effect, and (3) the irregular progress of magneto-resistance changes in low applied fields.

It is a pleasure at this time to acknowledge the contributions of several persons not already mentioned in the text of this report or in previous papers. Chief among these is my present assistant, Mr. L. R. Jackson, whose ingenuity, skill and patience have been unfailing. I am indebted to Dr. R. M. Bozorth and others at the Bell Telephone Laboratories for numerous services in connection with the procurement of materials. Dr. O. E. Buckley of the same organization has helped me frequently by critical comment and discussion, especially regarding the theory of ferromagnetic phenomena.[50]

[50] A brief note on this matter has been published: L. W. McKeehan, O. E. Buckley, Phys. Rev. [2] **33,** 636 (1929).