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Magnetoresistance and Domain Theory of Iron-Nickel Alloys

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Measurements of change of electrical resistivity with magnetization and with tension are reported for iron-nickel alloys containing 40 to 100 percent nickel. When the magnetostriction is negative (81 to 100 percent nickel), tension (σ) decreases resistivity, and magnetic field (H) increases it. Domain theory predicts the ratio σ/H at which the resistivity is equal to that of the unmagnetized specimen, and the theory is accurately confirmed. Measurements are made in transverse as well as longitudinal magnetic fields, and the difference between the resistances so measured is shown to be independent of the distribution of domains in the unmagnetized state; the erratic results reported in the literature are thus explained and avoided. When magnetostriction is positive, the limiting changes of resistivity with field and tension are sometimes found to be different; this is shown to be caused by the variation of magnetostriction with crystallographic direction.

INTRODUCTION

IT has been known for almost 100 years that the electrical resistivities of iron and nickel are increased when these materials are magnetized. It is now known that almost all ferromagnetic materials show this increase, which under certain conditions may amount to 15 percent or more. Closely associated with the change in resistivity due to magnetization is a change—an increase or a decrease—effected by tension within the elastic limit of the material. McKeehan[1] has studied both of these effects—called by him *magnetoresistance* and *elastoresistance*—in the face-centered iron-nickel alloys, and has pointed out the close relation that exists between elastoresistance and magnetostriction. More recently others[2] have discussed the domain theory of these phenomena.

The purpose of the present work has been (1) to extend the application of domain theory to these alloys, pointing out that certain new results can be accounted for quantitatively by theory, and (2) to measure the magnetoresistances of the iron-nickel alloys (40 to 100 percent nickel) and express them in such a way that the irregularities previously observed tend to disappear. The latter is accomplished by measuring the change in resistance when a specimen is placed first in a longitudinal field (field, H, parallel to electric current, i) and then in a transverse field ($H \perp i$); the difference between the resistivities is plotted against the percent of nickel.

The mechanism by which the change in resistance is produced is not well understood, and will not be discussed here.

METHOD OF MEASUREMENT

The alloys studied were of high commercial purity, and contained in addition to iron and nickel about 0.5 percent manganese, 0.4 percent cobalt, 0.02 percent carbon, and smaller amounts of sulfur and phosphorus. Specimens were thin tapes about 0.006×0.125 inch in section. They were straightened by stretching after a preliminary annealing, and were then annealed on a flat surface at 1050° to 1150°C in a hydrogen atmosphere. They cooled through 500°C at about 25°C/minute. Some of the alloys were subsequently held for 24 hours at 425°C to increase the amount of atomic ordering.

When tension was to be applied, specimens 60 cm in length were placed in a vertical position next to a heavy permalloy yoke used to reduce the demagnetizing factor. The magnetizing coil was placed around the middle 48 cm of the specimen, inside the yoke; and a search coil for ballistic measurements extended over the middle 15 cm. The specimen was held at its upper end by clamping it between the upper jaws of the yoke, and tension was applied to the specimen by hanging a weight on its lower end. A clearance

[1] L. W. McKeehan, Phys. Rev. **36**, 948–77 (1930). See also the earlier reports by H. D. Arnold and L. W. McKeehan, Phys. Rev. **23**, 114 (1924) and by L. W. McKeehan, J. Frank. Inst. **202**, 737–73 (1926).

[2] E. Englert, Ann. d. Physik **14**, 589–612 (1932); W. Döring, Ann. d. Physik **32**, 259–76 (1938); R. Becker and W. Döring, *Ferromagnetismus* (Verlagsbuchhandlung Julius Springer, Berlin, 1939).

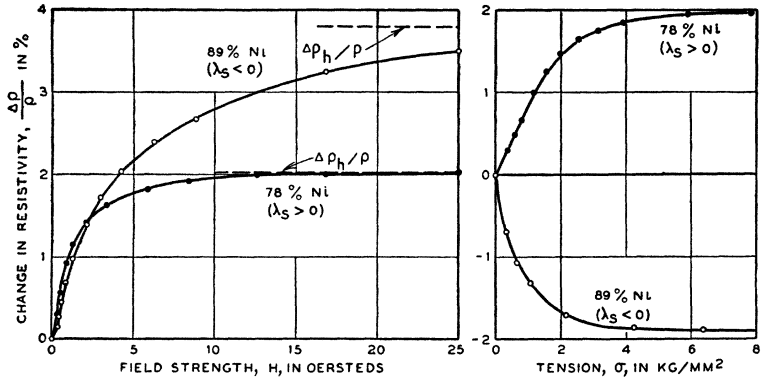

FIG. 1. A magnetic field usually causes an increase in resistivity. Tension increases resistivity of material when magnetostriction, λ_s, is positive, decreases it when magnetostriction is negative.

of a few tenths of a mm was left between the specimen and the lower jaws of the yoke to eliminate friction. Potential leads of fine wire were placed 40 cm apart.

When measuring transverse and longitudinal changes in resistance, with no tension applied, the specimen was 30 cm long, and was wrapped in paper and placed in a channel milled in a piece of brass $\frac{1}{2}$ inch wide. Pressing against the brass were the pole pieces of a large electromagnet* capable of delivering much more than the 20,000 oersteds actually used in the $\frac{1}{2}$-inch gap for measuring the transverse effect. The pole pieces extended over 15 cm of the specimen, and potential leads were symmetrically placed 10 cm apart. The demagnetizing factor for transverse magnetization was assumed to be equal to that for an ellipsoid having axes in the ratio 6:125: ∞; with the field applied, as it was, parallel to the axis of intermediate length, $N/4\pi$ is 0.047.

After measuring the resistance as a function of the transverse field, it was desirable to measure it immediately in a longitudinal field; consequently the brass holder containing the specimen, and its associated leads, were immediately lifted onto heavy upright pieces of iron placed 22 cm apart on the tops of the pole pieces of the magnet. Although the longitudinal field was now relatively small, measurements were made to about 2000 oersteds, more than sufficient to obtain the maximum increase in resistance.

The currents traversing the specimen varied up to 100 milliamperes. When necessary the current was reduced to successively lower values and the resistivity for zero current obtained by extrapolation. Potentials were read on a Leeds and Northrup Type K potentiometer. Experience showed that no special precautions were necessary for controlling the temperature of the specimen.

* Designed by Mr. P. P. Cioffi, to whom the author is indebted for its use.

QUALITATIVE DOMAIN THEORY

The effects of field (H) and tension (σ) are illustrated by new data shown in Fig. 1. Here 78 and 89 Permalloy are used as examples of materials of positive and negative magnetostriction, respectively. The increase in resistivity due to H approaches a limiting value designated $\Delta\rho_h$. The change of ρ with σ is an increase if the magnetostrictive fractional change in length at

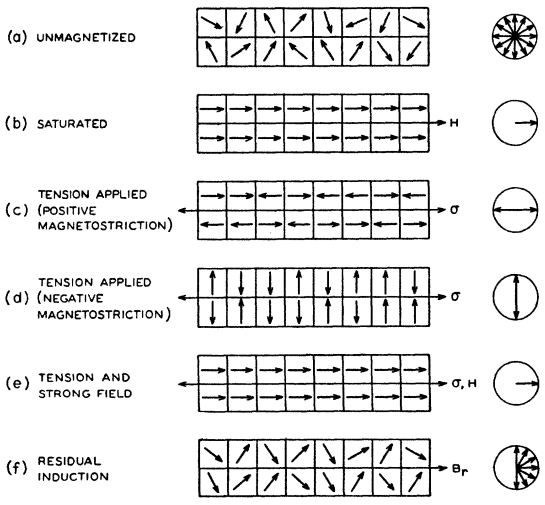

FIG. 2. Qualitative domain interpretation of effects of field and tension. Distribution of domains in various directions is represented by vectors in squares. In diagrams at right vectors have been moved to common origin.

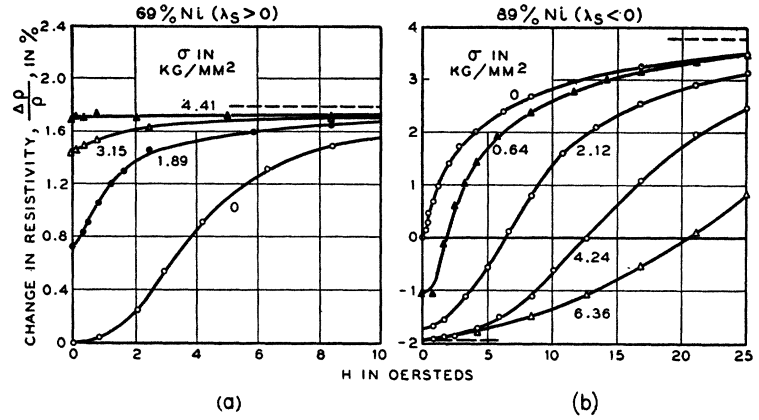

FIG. 3. Effect of magnetic field on resistivity of 69 and 89 Permalloys to which various tensions have been applied.

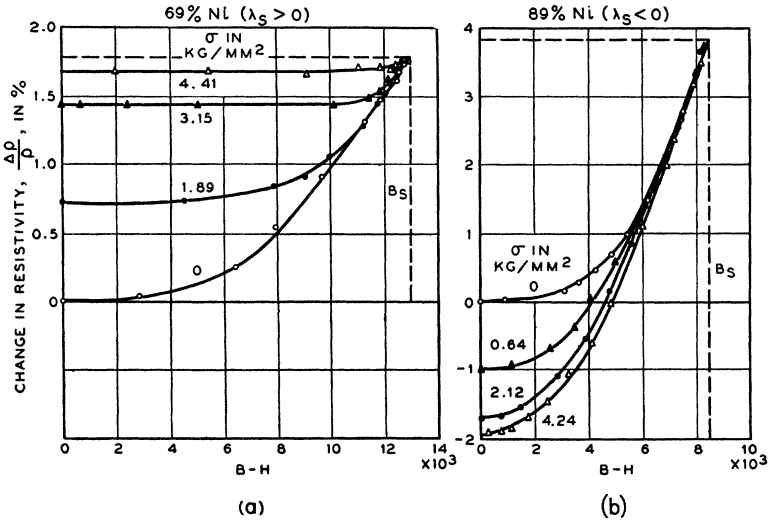

FIG. 4. Data like those of Fig. 3, plotted against $(B-H)$ instead of H.

saturation, λ_s, is positive, and a decrease if it is negative. A definite limit, $\Delta\rho_\sigma$, is observed for most of these alloys.

The domain interpretation of these results may be stated with the aid of Fig. 2. In the unmagnetized state the domains are oriented in many directions (*a*). A field aligns them so that their moments are parallel to the field—the "parallel" position (*b*). Tension causes the domains to take the two oppositely directed positions (*c*), parallel to the line of tension, if λ_s is positive, and positions perpendicular to the tension (*d*) if λ_s is negative. If the specimen is unmagnetized, the domains in a material with positive magnetostriction are aligned by tension so that there are equal numbers in the two opposite directions. Application of a strong field then reverses half of the domains. If tension is applied to a material with negative λ_s, subsequent application of a field will cause the domains to rotate continuously into the parallel position as the field is increased in strength to a high value.

The data of Figs. 3 and 4 can be interpreted in the manner just described. In 69 Permalloy ρ is increased by both H and σ, and the limit of ρ attained with H alone is the same as that with σ alone. When σ is applied first, and then H, Figs. 3(a) and 4(a) show that the magnetization increases for some time without change in ρ. As σ is increased the horizontal portion of the $\Delta\rho$ *vs.* $B-H$ curve increases in length until, in the limit, it constitutes the whole curve. Thus the 180° reversals, which do not alter the resistivity, become increasingly important and finally account for the whole change in magnetization.

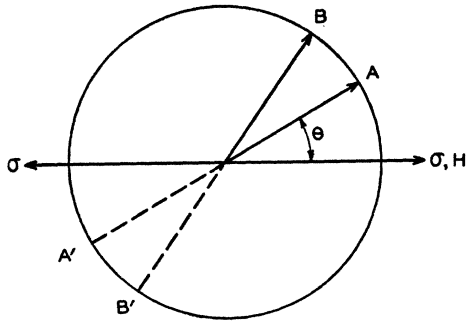

FIG. 5. Diagram showing how domain is rotated from initial position A to position B by tension σ, and rotated back to A by field H_0.

In 89 Permalloy ($\lambda_s<0$), σ and H oppose each other in their action; the effect of tension is to decrease, and magnetization to increase, the resistivity. The limiting change in resistivity due to σ is very close to $-\frac{1}{2}$ times that due to the field. That is,

$$\Delta\rho_\sigma/\rho \doteqdot -\tfrac{1}{2}\Delta\rho_h/\rho.$$

The curves of Fig. 4(b) have no horizontal portions, and this shows that at no stage in the magnetization is the 180° reversal the sole process occurring. On the contrary, evidence will be given below to show that under strong tension the whole change in magnetization is caused by domain rotation.

It will be noted that 89 Permalloy, when subjected to certain values of σ and H, has the same resistivity as in the initial demagnetized state. For this situation certain quantitative considerations are appropriate.

QUANTITATIVE RELATIONS

In materials with negative magnetostriction the effects of tension and longitudinal magnetic field are in opposite directions. It is possible to derive a relationship between values of tension and field strength which exactly compensate. This can be derived from Fig. 5. Here A shows the orientation of a domain in an unmagnetized, unstrained material. When a definite value of the tension, σ_0, is applied as indicated, the orientation will change to that indicated at B. Superposition of a field will then rotate the domain toward its original orientation, which it will attain at some specific value of the field-strength, H_0. Domains oriented originally at A' will be rotated by σ_0 to B', and when H_0 is applied they will presumably rotate suddenly by 180° (i.e., invert) and occupy the same final position A. In this final position it will be subject to the same balanced forces of crystal anisotropy and internal strain as existed in the demagnetized state, that is, the resultant of these forces will be zero. The relationship between these compensating values of σ_0 and H_0 should then be amenable to calculation by domain theory without having to take into account the complicating influences of crystal anisotropy and internal strain.

The domain energy associated with σ and H is given[3] by the relation

$$E=-\tfrac{3}{2}\lambda_s\sigma\cos^2\theta-HI_s\cos\theta,$$

in which θ is the angle between the local magnetization, I_s, and the common axis of σ and H. The equilibrium will occur when the energy is a minimum given by

$$dE/d\theta=0;$$

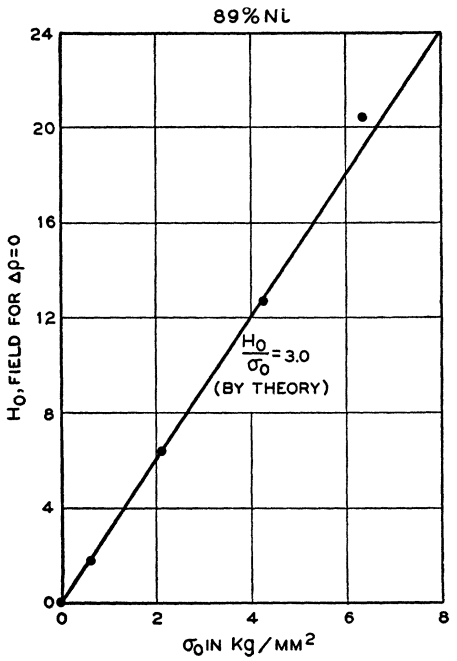

FIG. 6. Comparison of theory (straight line) and experiment (points). Application of tension, σ_0, decreases resistivity, ρ; H_0 is field strength necessary to bring ρ back to original value.

[3] Becker and Döring, reference 2.

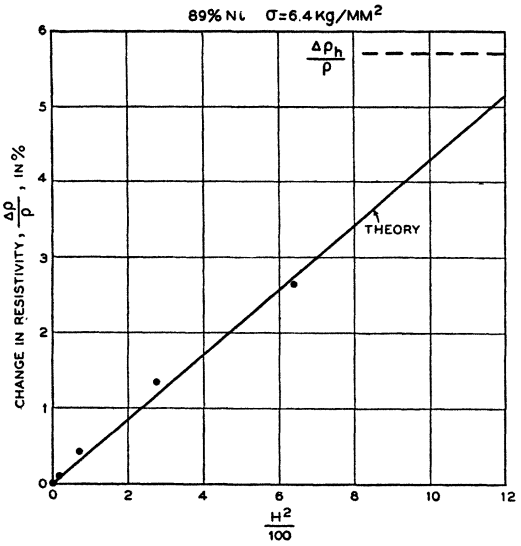

FIG. 7. Change of ρ with H when specimen is subject to high tension. Systematic departure from straight line is caused by forces not taken into account by theory.

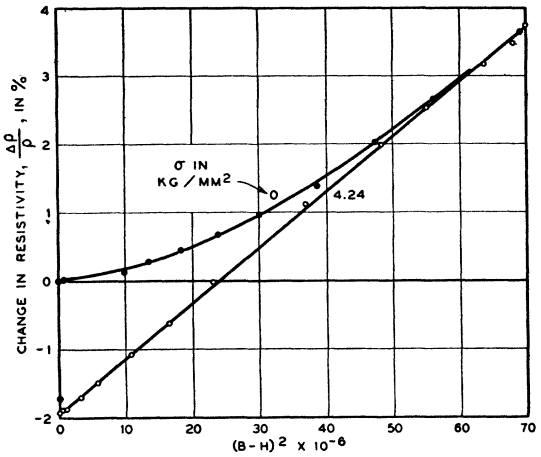

FIG. 8. In specimen under tension, $\Delta\rho$ increases linearly with square of magnetization (rotation process).

hence H_0 must be related to σ_0 as follows:

$$H_0/\sigma_0 = -3(\lambda_s/I_s)\cos\theta,$$

For 89 Permalloy the values of the constants λ_s and I_s are known to be -13×10^{-6} and $8300/(4\pi)$, respectively. For domains orientated uniformly over a hemisphere $\langle\cos\theta\rangle_{Av}=\frac{1}{2}$. If σ_0 is now expressed in kg/mm² and H_0 in oersteds, this relation reduces to

$$H_0/\sigma = 3.0 \text{ oersteds mm}^2/\text{kg}.$$

The corresponding line is drawn in Fig. 6. There the circles represent the values of H_0 and σ_0 corresponding to the intercepts on the H axis of the curves of Fig. 3(b). The agreement is well within the combined limits of accuracy of the data of the experiment and the numerical values of the constants of the equations.

Domain theory may also be applied, with some approximations, to the experiment in which σ is large enough to cause $\Delta\rho$ to attain its limit $\Delta\rho_\sigma$. Then θ is 90° for all the domains, and the disturbing effects of crystal anisotropy and internal stress are small, and can be neglected in comparison with the externally applied stress. It is known that changes in resistivity due to domain orientation are proportional to $\cos^2\theta$, a relation necessitated by the observation that when a material is saturated the change in resistivity, $\Delta\rho_h$, is the same whether the electric current used for measurement of ρ is parallel or antiparallel to H. If the zero of change of resistivity is chosen when σ is already applied and H not yet applied, the relation

$$\Delta\rho = \Delta\rho_1\cos^2\theta$$

therefore holds. This may be combined with the previously used expression containing $\cos\theta$ to give

$$\Delta\rho = \Delta\rho_1 I_s^2 H^2/(9\lambda_s^2\sigma^2).$$

Using the constants for 89 Permalloy this reduces to

$$\Delta\rho/\rho = 43\times10^{-6}H^2,$$

for the conditions of the experiment, in which $\sigma=6.36$ kg/mm². Since $\Delta\rho/\rho$ for large values of H approaches a definite limit, this relation applies only to values of $\Delta\rho/\rho$ that are well below this limit.

This equation is compared with the data in Fig. 7. The discrepancies are in the expected direction. In low fields, before the domains have been turned by the field from the transverse position ($\theta=90°$) to the equilibrium position occupied in the unmagnetized state, the forces due to internal strains and crystal anisotropy will tend to turn the domains from their 90° positions and so aid the field and cause $\Delta\rho$ to be higher than the theoretical value. After the domain has passed through this equilibrium orientation, which it possessed when the field

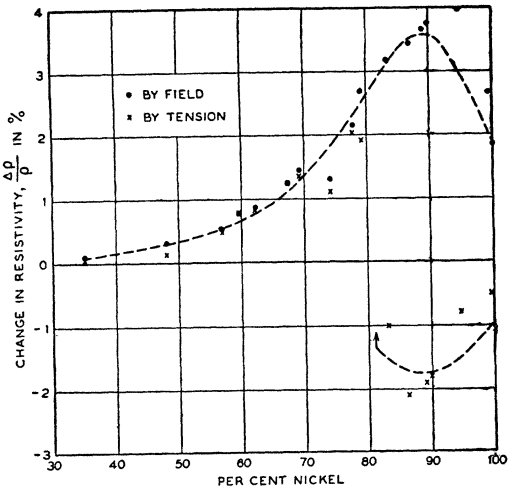

FIG. 9. Limiting effects of field and tension on various Permalloys, according to Shirakawa, Yamanaka, and the author. Broken line shows changes expected on simple theory.

strength had the value given by H_0 above, the internal strain and crystal anisotropy should cause $\Delta\rho$ to fall below the theoretical value, as the data of Fig. 7 show that they do. These forces cause $\Delta\rho$ to approach its limiting value $\Delta\rho_1$ asymptotically.

According to this view of the mechanism of change of magnetization and its effect on resistivity, the domains should assume the orientations they possessed when the specimen was unmagnetized (e.g., A in Fig. 5), or at an orientation 180° therefrom (A instead of A'), when the material as a whole is magnetized to just half of saturation. That is, it should be observed that $I/I_s=0.5$ when $\Delta\rho=0$. Actually I/I_s is somewhat greater than 0.5, almost 0.6. This difference could be caused by a non-random distribution of domain orientations in the unmagnetized condition, due to preferred orientation of crystals or internal strains.

When a sufficient tension is applied to a material with negative magnetostriction the domains are aligned transversely, and subsequent magnetization is accomplished by domain rotation. The induction is then proportional to cos θ,

$$B-H=B_s\cos\theta.$$

Since the change in resistivity is proportional to $\cos^2\theta$, it is, therefore, proportional to $(B-H)^2$. This is confirmed by experiment, as shown in Fig. 8; and such a linear relation may be interpreted, as previously pointed out by Gerlach[4] as evidence that the magnetization proceeds by a purely rotational process. It also shows that the $\cos^2\theta$ term is sufficient to describe the change of resistivity of a domain with orientation, and that no term of higher power is necessary.

IRON-NICKEL SERIES

The maximum changes in resistivity due to magnetization and to tension, as observed by many experimenters, have varied considerably from specimen to specimen. Data obtained by Shirakawa,[5] Yamanaka,[6] and the author, plotted in Fig. 9, show the wide range of values obtained, and similar variations were observed by McKeehan[1] in unsaturated alloys. It was believed that the non-uniformity of the results was caused by the differences in the initial condition of the specimens, resulting mainly from differences in crystal orientation and internal strain. Therefore, it seemed appropriate to measure a given specimen first in a longitudinal and then in a transverse field and plot the difference of the resistivities, $\rho_h-\rho_t$. This should be of rather fundamental importance because it represents the maximum change in resistivity that can result from domain orientation, and is independent of the initial condition of the particular specimen used. It would not be expected to vary with heat treatment unless phase transformations or atomic ordering occur.

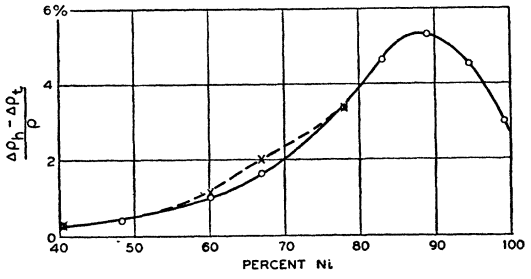

FIG. 10. Difference between longitudinal and transverse changes in resistivity. Solid line is for alloys cooled in normal way, broken line for alloys cooled very slowly to develop superstructure.

[4] W. Gerlach, Ann. d. Physik **12**, 849–64 (1932).
[5] Y. Shirakawa, Sci. Rep., Tohoku Imp. Univ. **27**, 485–531 (1939).
[6] N. Yamanaka, Sci. Rep., Tohoku Imp. Univ. **29**, 36–68 (1940).

Results of these measurements are given in Fig. 10, and lie on a relatively smooth curve. The maximum of over 5 percent occurs near 90 percent nickel, and the effect is relatively small in the low nickel alloys. The change in resistivity in alloys near $FeNi_3$ is increased by the ordering resulting from heating for 24 hours at 425°C.

Two-thirds of $\rho_h - \rho_t$ is shown (in percent) by the broken line of Fig. 9. This represents the value of $\Delta\rho_h$, to be expected only when the domains are distributed at random in the unmagnetized state and when there is negligible dependence of resistivity on the orientation of the domain with respect to the crystal axes. In that case the following relations hold[7]

$$\Delta\rho = \tfrac{3}{2}\Delta\rho_h(\cos^2\theta - \tfrac{1}{3}),$$

$$\Delta\rho_t = -\tfrac{1}{2}\Delta\rho_h,$$

$$\Delta\rho h = \tfrac{2}{3}(\rho_h - \rho_t),$$

$$\Delta\rho_\sigma = \Delta\rho_h \quad (\lambda_s > 0),$$

$$\Delta\rho_\sigma = \Delta\rho_t = -1/2\Delta\rho_h \quad (\lambda_s < 0).$$

The broken line in the lower part of Fig. 9, extending from 81 to 100 percent nickel, shows the values of $\Delta\rho_\sigma$ expected according to the last relation. In the alloys containing 69 and 89 nickel there is little if any departure from these ideal conditions, as shown by the data of Figs. 9 and 10. Substantial departures, however, have been observed[8] for the alloys containing low nickel (e.g., 50 percent) and high nickel (near 100 percent) and for those lying near the zero-magnetostriction point (81 percent). The high nickel anomaly, with $\Delta\rho_\sigma \neq -\frac{1}{2}\Delta\rho_h$, has been shown by Döring[9] to be caused by crystal anisotropy. In many other alloys, having $\lambda_s > 0$, it is found that $\Delta\rho_\sigma \neq \Delta\rho_h$, a fact to be discussed in the next section.

NON-EQUIVALENCE OF FIELD AND TENSION

As remarked above, the magnetoresistance and elastoresistance do not always approach the same limits, $\Delta\rho_h$ and $\Delta\rho_\sigma$, as simple theory indicates that they should when the magnetostriction is positive. This cannot be attributed to a non-

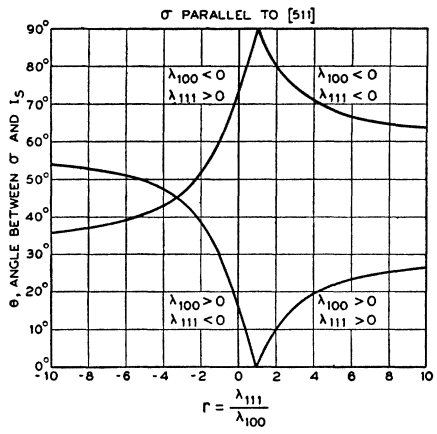

FIG. 11. Angle θ between directions of magnetization (I_s) and tension (σ) when tension is applied parallel to a [511] crystallographic direction. Theoretical.

random distribution of domains in the unmagnetized conditions, and it now appears that it is to be expected when the magnetostriction varies with crystallographic direction, as it does in these alloys. Lichtenberger's measurements[10] show that between 35 and 45 percent nickel the magnetostriction (λ_s) is positive in the [111] direction ($\lambda_{111} > 0$) and negative in the [100] direction ($\lambda_{100} < 0$). In a polycrystalline specimen tension will, therefore, increase the resistivity of those crystals that have [111] directions lying near the axis of tension, and decrease it in those having [100] near the axis. The resultant $\Delta\rho_\sigma$ will thus be less than $\Delta\rho_h$. Similarly Lichtenberger's curves show that λ_{111} and λ_{100} are opposite in sign between about 80 and 85 percent nickel; and this range may be expected to vary with heat treatment, which affects the amount of atomic order. In other alloys, except those near 60 and 85 percent nickel, λ_{111} and λ_{100} have the same sign but are substantially different in magnitude, and this difference prevents σ from causing complete alignment of all the domains by tension.

In a quantitative evaluation of the effect of anisotropic magnetostriction we start with the expression for the magnetic strain energy of a domain, as given by Becker and Döring.[2] Let α_1, α_2, α_3 be the direction cosines of the magnetization (I_s) of the domain, and γ_1, γ_2, γ_3 the direction cosines of the stress (σ) with respect to the

[7] Englert, and Becker and Döring, reference 2.
[8] Yamanaka, reference 6, and the author.
[9] Döring, reference 2.

[10] F. Lichtenberger, Ann. d. Physik **15**, 45–71 (1932).

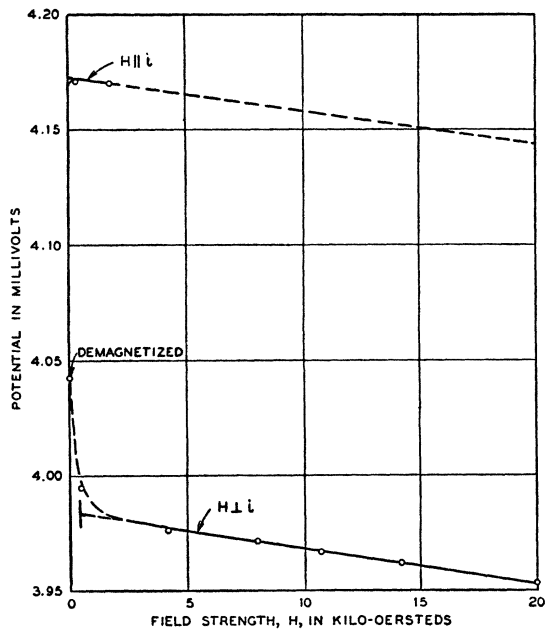

FIG. 12. Data from which changes in resistivity of 83 Permalloy, in longitudinal and transverse fields, are determined. Ordinate shows direct reading on potentiometer; current through specimen being held constant. Change in spontaneous magnetization causes the linear part of the decrease in ρ.

crystal axes. Then the energy is

$$F_\sigma = -\frac{3\sigma}{2}[\lambda_{100}(\alpha_1^2\gamma_1^2+\alpha_2^2\gamma_2^2+\alpha_3^2\gamma_3^2) +2\lambda_{111}(\alpha_1\alpha_2\gamma_1\gamma_2+\alpha_2\alpha_3\gamma_2\gamma_3+\alpha_3\alpha_1\gamma_3\gamma_1)].$$

The problem is first to find the angle, θ, between I_s and σ for any given set of values of λ_{100}, λ_{111}, and the γ's, and the corresponding α's which make F_σ a minimum. Then it is desired to evaluate $\cos^2\theta$ for these conditions and find its average value for all possible values of the γ's. This makes it possible to calculate the ratio, $\Delta\rho_\sigma/\Delta\rho_h$, for a polycrystalline wire having crystals oriented at random, when σ and H are applied separately along the wire axis.

The determinations of the α's which minimize F_σ for a given set of values of λ_{100} and λ_{111} and the γ's, can be accomplished as follows: For convenience set $r=\lambda_{111}/\lambda_{100}$ and $Q=-2F_\sigma/3\sigma$. Then it is well known that the quadratic form in the α's,

$$Q=\lambda_{100}[\alpha_1^2\gamma_1^2+\alpha_2^2\gamma_2^2+\alpha_3^2\gamma_3^2 +2r(\alpha_1\alpha_2\gamma_1\gamma_2+\alpha_1\alpha_3\gamma_1\gamma_3+\alpha_2\alpha_3\gamma_2\gamma_3)],$$

subject to the condition $\sum\alpha_i^2=1$, can be reduced, for any r, to the form

$$Q_1=\lambda_{100}(\sum\lambda_i y_i^2)$$

by means of the real orthogonal transformation

$$\alpha_i=\sum b_{ij}y_j.$$

The numbers λ_i are all real and are roots of the secular determinant

$$|Q-\lambda I|=0$$

or

$$\begin{vmatrix} \gamma_1^2-\lambda & r\gamma_1\gamma_2 & r\gamma_1\gamma_3 \\ r\gamma_1\gamma_2 & \gamma_2^2-\lambda & r\gamma_2\gamma_3 \\ r\gamma_1\gamma_3 & r\gamma_2\gamma_3 & \gamma_3^2-\lambda \end{vmatrix}=0.$$

The energy and direction of magnetization will be given by the largest eigenvalue if $\lambda_{100}>0$ (and the smallest if $\lambda_{100}<0$) and the corresponding eigenvector.[11]

The solution can be seen from inspection when the stress is parallel to any of the principal crystallographic directions [100], [110], and [111]; for these $\theta=0$ or 90° for all values of λ_{100} and λ_{111}. As an example of the effect expected in other directions, θ is plotted in Fig. 11 for the [511] direction for various ratios, $r=\lambda_{111}/\lambda_{100}$, and for positive and negative values of λ_{100}.

Lichtenberger's data show that $\lambda_{100}>0$, $r=10$, for some composition in the neighborhood of 75 to 80 percent nickel, the exact composition depending on the rate of cooling of the alloy after annealing.[12] Under these conditions the value of $\cos^2\theta$ averaged over the unit sphere (by a graphical method) is about 0.93, and this means that tension should effect a change of resistivity $\Delta\rho_\sigma=(3/2)(0.93-1/3)\Delta\rho_h=0.89\,\Delta\rho_h$. This ratio 0.89 is not far from the ratio 0.85 observed by Yamanaka[6] for 74 percent nickel (see Fig. 9); a definite comparison for an alloy of given composition is not possible in view of the uncertainty in the values of λ_{111} and λ_{100} for a given specimen.

A somewhat better comparison between theory and experiment may be made for the 35 percent nickel alloy. Here $\lambda_{100}<0$, $r\doteq-4$, according to Lichtenberger's data. The calculated value of $\langle\cos^2\theta\rangle_{Av}$ is 0.8, from which can be derived the

[11] R. Courant and D. Hilbert, *Methoden der Mathematischen Physik* (Verlagsbuchhandlung Julius Springer, Berlin, 1924), Vol. 1, p. 20.
[12] E. M. Grabbe, Phys. Rev. **57**, 728–34 (1940).

ratio $\Delta\rho_\sigma/\Delta\rho_h=0.7$, whereas the observed[6] ratio is 0.5.

Although the agreement between these values, and between observed and calculated values considered above, is not as good as might be desired, it appears to be adequate to establish the explanation here proposed.

UNANNEALED SPECIMENS

Measurements of magnetoresistance were made on two specimens of unannealed material, severely cold rolled, containing 67 and 89 percent nickel. The purpose was to find out whether or not $\Delta\rho_h$ and $\Delta\rho_h-\Delta\rho_t$ were the same as in the annealed material. The results are given in Table I.

It is apparent that the severe cold rolling of the material has not changed the total magnetoresistance, equal to the difference between the longitudinal and transverse effects. However, the effect of cold rolling on the longitudinal effect, $\Delta\rho_h$, is substantial and shows that in the demagnetized state the domains are not oriented at random. The low value of $\Delta\rho_h$ indicates that there is a preponderance of domains oriented nearly parallel to the axis.

A similar effect of cold working on lowering the *magnetostriction* of nickel[13] and of 68 Permalloy[14] has been observed, and the cold rolling of iron[15] has been found to increase its (positive) magnetostriction. In the almost identical 67 and 68 Permalloys the effect of the working is the same —a reduction of about 50 percent—in both magnetostriction and magnetoresistance. This is to be expected in view of the close relation between these properties.

The non-random distributions of domain orientations in all of these materials are consistent with the data[16] on the directions of easy magnetization in rolled sheets. These directions are parallel to the direction of rolling in nickel and 78 Permalloy, and at 45° from this direction in the plane of the sheet, in iron. In unmagnetized nickel, therefore, the domains tend to be oriented parallel to the direction of easy magnetization, and when a field is applied they first change orientation by 180°, without affecting magnetostriction or resistivity. In higher fields they rotate into more exact alignment with the field and so exhibit a limited magnetostriction and magnetoresistance. A similar consideration of iron shows that an increased positive magnetostriction is to be expected.

TABLE I. Longitudinal magnetoresistance, $\Delta\rho_h$ (demagnetized state to saturation), and total magnetoresistance, $\Delta\rho_h-\Delta\rho_t$ (transverse to longitudinal) of unannealed and annealed material.

Percent nickel	Treatment	$\Delta\rho_h$	$\Delta\rho_h-\Delta\rho_t$
67	Unannealed	0.5%	1.9%
67	Annealed	1.2	1.9
89	Unannealed	2.4	5.3
89	Annealed	3.7	5.3

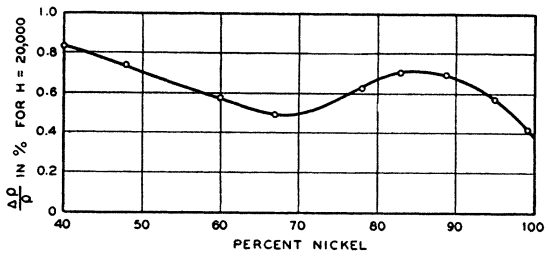

FIG. 13. Change in resistivity due to change in spontaneous magnetization in field of 20,000 oersteds.

Little is known of the distribution of stresses or crystal orientations that could cause the direction of rolling to be a direction of easy magnetization in these alloys. The effect of crystal orientation is very weak in 67 Permalloy, and the sign of the magnetostriction is opposite in 67 Permalloy and in 89 Permalloy (or nickel), so that neither crystal orientations nor internal strains appear to give an appropriate explanation. The same problem has been discussed by Conradt and Sixtus.[17]

HIGH FIELDS

The measurements in transverse fields were carried to $H=20{,}000$ oersteds. It has already been shown by Gerlach[18] that an increase in spontaneous magnetization will cause a decrease in resistivity. Since the fields used in these experiments are large enough to produce at room temperature a definite change in spontaneous

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magnetization, and, therefore, in resistivity, it was necessary to separate this effect from the change in restivity due to domain orientation. The separation was made by the method used by Englert,[19] by extrapolating the ρ *vs.* H curve, as illustrated in Fig. 12 for 83 percent nickel. The points for transverse magnetization lie on a straight line permitting easy extrapolation to the demagnetizing field corresponding to saturation; for the specimen of tape used this was small, $(N/4\pi)B_s=0.047\times9800=450$. The same slope of ρ *vs.* H curve was used to extrapolate the longitudinal measurements to $H=0$.

The slope of the ρ *vs.* H line for nickel was nearly the same as that reported by Englert. The slopes for the other specimens are recorded in Fig. 13, as percent change in ρ for $H=20{,}000$ oersteds. The results are probably not accurate to less than 0.1 percent, but appear to lie on a smooth curve. The explanation of the shape of the curve is not apparent. On the one hand one might expect the effect to be large when the curie point is low, as it is at each end of the range of alloys studied, because there the change in spontaneous magnetization with field is relatively large. On the other hand, near 70 to 75 percent nickel the crystal anisotropy is zero, and order-disorder phenomena are observed, and there may be some connection, not now established, between these and the effect of spontaneous magnetization on resistivity.

I am indebted to Dr. C. L. Dolph and Miss C. L. Froelich for assistance with the mathematics and computations involved in the solution of the energy equation.

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The Velocity of Sound in Hydrogen when Rotational Degrees of Freedom Fail to Be Excited

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The velocity of sound in parahydrogen, normal hydrogen, and 50 percent para-50 percent orthohydrogen mixtures has been observed at several temperatures, and over a range of frequency to pressure ratio from one to 60 megacycles per atmosphere. Dispersion attributed to failure of the rotational degrees of freedom to follow the temperature associated with the translational degrees of freedom has been observed with all mixtures and at every temperature at which observations were made. Measurements at two different frequencies for similar samples at the same temperature indicate that frequency and pressure affect the velocity of sound only as the quotient, frequency/pressure, with the exception of small corrections that must be applied because hydrogen is not a perfect gas. Experiments indicate that the dispersion occupies a greater range of frequency to pressure than would be expected if the rotational specific heat behaved as a simple relaxation phenomenon. It is shown that a simple relaxation phenomenon is not to be expected, and that the dispersion in parahydrogen can be characterized, approximately, by two relaxation frequency to pressure ratios, one for the rotational transition 0–2, and another for the transition 2–4. An expression for these relaxation frequency to pressure ratios, that roughly fits the observations, is derived on the basis of some assumptions about the collision process.

CHANGES of sound velocity in some gases with variation of the frequency to pressure ratio have been known for a number of years. These have been attributed to failure of the internal degrees of freedom of the molecules to follow temperature changes in the sound wave. The first phenomenon of this type to be observed was associated with vibrational degrees of freedom. In this respect carbon dioxide has been extensively investigated.[1]

Recently in this laboratory E. S. Stewart[2] observed a similar phenomenon associated with

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