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THE EFFECT OF TENSION ON THE CHANGE OF THERMOELECTROMOTIVE FORCES BY MAGNETIZATION.

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SYNOPSIS.

Combined Effect of Tension and Magnetic Field on Thermoelectromotive Force and Resistance of Some Ferro-magnetic Metals.—Wires 10 cm. long and 0.15 cm. in diameter were each held in heavy brass clamps and stretched while placed axially in a vertical solenoid. While determining the electromotive forces, one end was kept at 100°, the other at 0° C. In the case of *nickel*, the effect of tension on the change in resistance (ΔX) and in thermoelectromotive force (ΔE) produced by a longitudinal magnetic field is a decrease for weak fields but an increase for larger fields. For a given tension, the ratios of ΔX to ΔE and to the magnetic change of length (ΔL) are independent of the field strength and therefore seem to depend on the same factor. *Pure iron* shows a parallelism between the effects of tension on ΔE and ΔL; with increasing tension the curves for ΔE as function of the field shift downward so that for sufficiently large tensions ΔE becomes negative throughout. The curve for ΔE may be considered the sum of two effects, associated with two forms of iron, one of which is proportional to ΔL and is affected by tension more than the other. The behavior of *iron-copper alloys* is qualitatively similar to that of iron. *Iron-nickel alloys* behave like iron until the per cent. of Ni is more than 7 when they tend to behave more and more like Ni. For both series of alloys the change of ΔX due to tension is always a decrease.

Relation between the Hall Constant, Specific Resistance and Fractional Change of Thermoelectromotive Force Produced by a Magnetic Field in a Series of Iron-copper Alloys is pointed out. The three properties vary with copper content in a similar way, all showing a cusp for 1.5 per cent. copper.

Electron Theory of Conductivity and Thermoelectromotive Force.—In a *discussion* of the above results it is shown that neither the gas-free theory as given by Heaps nor Bridgman's gap theory explains them satisfactorily. The decrease in resistance with increase of length would be expected, however, if the number of free electrons varies in an inverse manner with the atomic frequency; and ΔE would vary with magnetic field and tension if the atomic frequency and the number of free electrons are not the same functions of the magnetic field at different temperatures and tensions.

THE influence of tension on the resistance, length, permeability and elastic constants of ferromagnetic substances in longitudinal magnetic fields has been frequently studied. Similar observations do not seem to have been made on the effect of tension on the changes in the thermoelectromotive forces produced by such a magnetic field. In view of the dependence of the resistance and the thermoelectromotive force on each other and on the elastic and magnetic properties of the substance, it seemed of interest to study the variation of the thermoelectromotive forces produced by a longitudinal magnetic field when the substances were sustaining tensions of different amounts.

Methods of Observation.—The specimens to be studied were in the form of thin wires about 10 cms. in length and .15 cm. in diameter. These wires after being fastened to heavy brass rods were suspended axially in a solenoid which was 40 cms. long. The wires lay near the center of the solenoid where the magnetic field was nearly uniform. At a point just below or above the junction of the brass rods and the wires there was soldered a copper wire which with the specimen formed a thermal couple. One junction was kept in a mixture of ice and water and the other in steam at atmospheric pressure. The tensions were applied to the specimens by placing different weights on a scale pan suspended from the wire.

The thermoelectromotive force arising from the couple was nearly balanced by connecting the copper lead wires in the usual manner to a Wolff potentiometer. The thermoelectromotive forces set up by the longitudinal magnetic field were determined by noting the deflection of a sensitive Leeds and Northrup galvanometer of the d'Arsonval type. From this deflection together with the sensibility of the galvanometer the change in thermoelectromotive force produced by the longitudinal magnetic field was calculated. The total electromotive force of the couple was read directly from the potentiometer.

In order to compare the effect of tension on the change of thermoelectromotive force with the effect of tension on the longitudinal change of resistance, some observations were made on the change of resistance in a magnetic field in these same wires when the wires were sustaining loads of different amounts. The measurements of the changes of resistance were made by means of a Kelvin double bridge. The bridge was balanced as nearly as possible when there was no magnetic field in the solenoid. The deflection of the galvanometer resulting from the establishment of the magnetic field in the solenoid gives a measure of the change of resistance in the specimen resulting from the action of the magnetic field. To calculate the change of resistance from this deflection it is necessary to know the current in the specimen and the sensitivity of the galvanometer besides the resistances entering into the network of the bridge. For resistances of the magnitude used in these experiments the change of resistance can be calculated with sufficient accuracy from the formula,[1]

$$\frac{\Delta X}{X} = \frac{K}{PI_b}\left[R_g \left(1 + \frac{N}{M} \right) + 2N \right] D,$$

where K = current to produce 1 cm. deflection,
D = deflection of galvanometer in cms.,
R_g = resistance of galvanometer,
I_b = current in the unknown resistance,
N, M and P = resistances in the arms of bridge.

Besides nickel and iron a number of alloys of iron and copper and also some alloys of nickel and iron were studied. These are the same alloys which were used by the author in a study of the Hall effect and the Nernst effect.[2] They were prepared by Burgess and Aston[3] from exceptionally pure metals. The observations on the change of resistance were made at room temperature. The changes in the thermoelectromotive forces are the changes which arise when one junction is at 0° C. and the other at 100° C. The tensions which have been recorded on the following curves have been expressed in kilograms per sq. mm.

The curves in Fig. 1 show the change of resistance and the change of

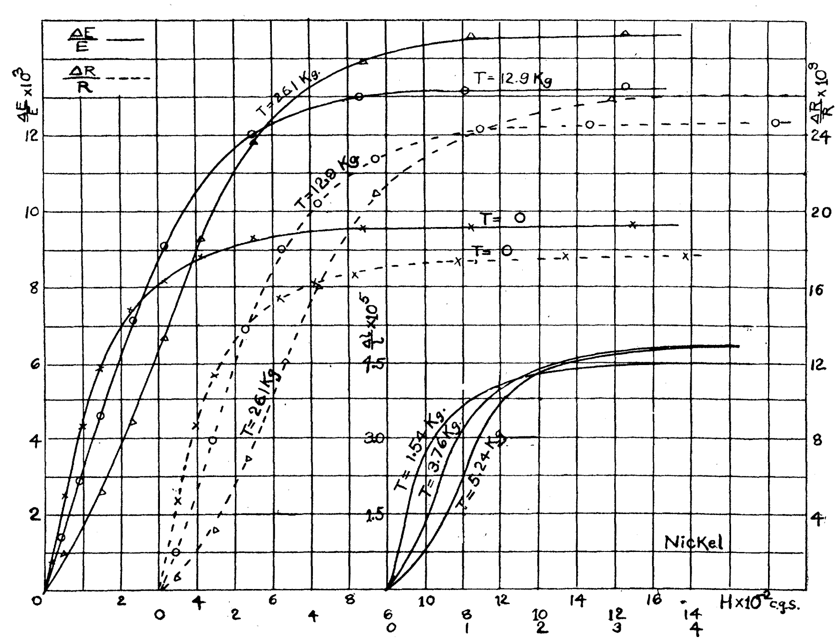


Fig. 1.

[1] Laws, Electrical Measurements, p. 194.
[2] Smith, Phys. Rev. (2), 17, 23, 1921.
[3] Burgess and Aston, Met. and Chem. Eng., 8, 19, 1910.

thermoelectromotive force in nickel under different loads in a longitudinal magnetic field. This nickel was of unknown purity. It was obtained from Eimer and Amend as pure nickel. For the sake of comparison there has been plotted in this same figure the fractional change of length in nickel in a longitudinal magnetic field. The data for these curves were taken from the work of Honda and Terada.[1] These curves have been plotted above the horizontal axis without regard to the sign of the effect whether positive or negative. The magnetic field produces an increase in the resistance, a decrease in the thermoelectric height against copper and a decrease in length. An examination of these curves shows that the change in thermoelectromotive forces produced by a longitudinal magnetic field behave in almost exactly the same way in which the change of resistance and the change of length behave. The effect of tension is to decrease the effect of the magnetic field on the resistance, length and thermoelectromotive forces for smaller magnetic fields. On

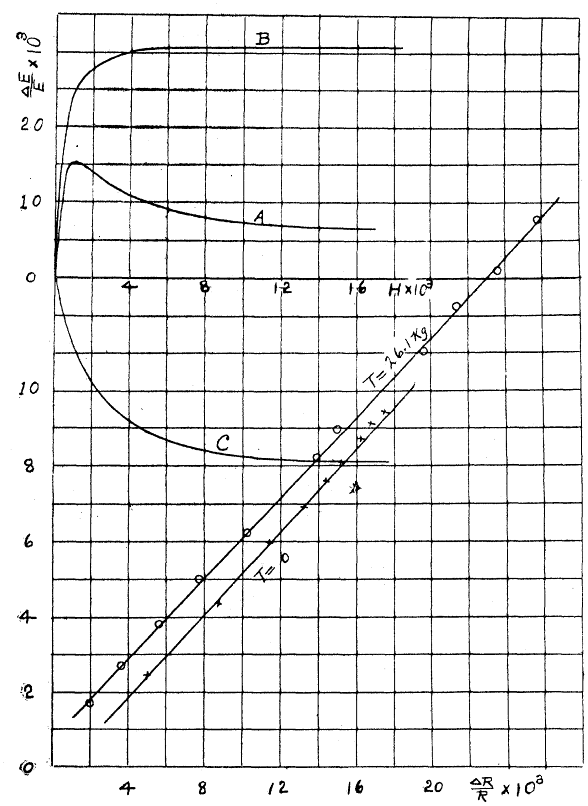


Fig. 2.

[1] Honda and Terada, Phil. Mag. (6), 13, 36, 1907.

the other hand for the larger magnetic fields these changes are greater for large tensions than for small tensions.

In the lower half of Fig. 2 the fractional change of resistance for a particular magnetic field has been plotted against the fractional change of thermoelectromotive force, for the case in which the wire is unloaded and for the case in which the wire sustains the maximum load. A proportionality is found between these two changes. The factor of proportionality is a function of the tension. Heaps[1] has pointed out that there is in nickel a proportionality, except for small magnetic fields, between the change of resistance and the change of length. To these observations is added the fact that in nickel the change in thermoelectromotive force is proportional to both the change of resistance and the change of length. From this it is clear that whatever factors determine the change of length of nickel, in much the same way they determine the change of resistance and the change of thermoelectromotive force. Grondall,[2] however, failed to find a simple relation between the change in length and the change in thermoelectromotive forces in Heusler alloys.

Similar observations on pure iron show a parallelism between the change of thermoelectromotive force produced by the magnetic field when the wire sustains different loads and the change in length under corresponding conditions. The curves at the bottom of Fig. 3 are taken

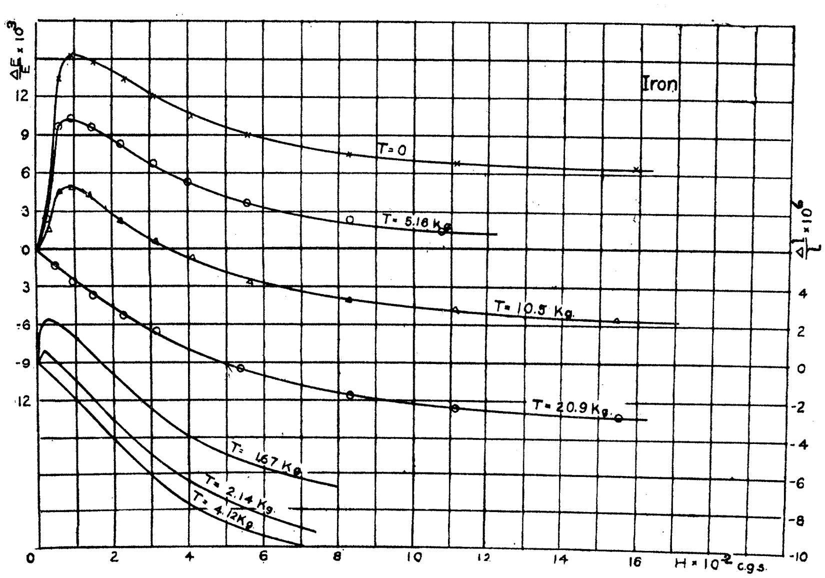


Fig. 3.

[1] Heaps, Phys. Rev. (2), 6, 34, 1915.
[2] Grondall, Phys. Rev. (2), 4, 325, 1914.

from the work of Honda and Terada. A comparison of these curves with those above them shows that the effect of tension on the change of length in a magnetic field and its effect on the change in the thermoelectromotive force are quite similar. In each case the application of tension decreases the initial effect. When the tension is sufficiently large the direction of the change is reversed. The initial change of the length is an elongation and this at sufficiently large fields and tensions becomes a contraction. The initial change in the thermoelectromotive force is an increase in the thermoelectric power with respect to copper. For sufficiently large magnetic fields and tensions this reverses and becomes a decrease. An increase in length is associated with increase in thermoelectric power. The larger the tension the smaller the magnetic field at which this reversal takes place. The reversal of the direction of the change of length takes place for smaller tensions and smaller magnetic fields than those necessary for the reversal of the direction of the change of thermoelectromotive force. This may be due to the fact that the two changes were not studied in the same specimen of iron. For sufficiently large tensions the curve starts downward from the origin and the change of length is always a contraction and the thermoelectric power is always decreased.

The linear relation between the change of length, resistance and thermoelectromotive force found in the case of nickel does not hold in the case of iron. The curves (Fig. 9) showing the relation between the change of resistance and the magnetic field have the usual form for iron. The application of tension causes a decrease in the change of resistance produced by the magnetic action. In nickel tension caused a decrease in the change of resistance which was later followed by an increase at sufficiently large magnetic fields. Heaps[1] found a proportionality between the change of length and the change of resistance in a longitudinal magnetic field. The curve which he gives to show the relation between the change of length and the magnetic field is very different from those given by other observers except for one case recorded by Bidwell.[2] The reason for the discrepancies between the observations of Heaps and those of other observers is not evident, unless it be due to polymorphism of iron and in one of these forms the change is positive and in the other it is negative.

Now each of these curves showing the relation between the change of length and the change of thermoelectric power in iron in a longitudinal magnetic field can be arbitrarily broken up into two parts as shown in the upper half of Fig. 2. This is equivalent to regarding the magneto-

[1] Heaps, PHYS. REV. (2), 6, 34, 1915.
[2] Bidwell, Proc. Roy. Soc., 56, 1894.

strictive effect as well as the change in thermoelectric power as made up of two parts, one positive and the other negative. One of these parts is represented by Curve B and the other by Curve C.

The sum of the ordinates of Curve B and Curve C gives the ordinates of the observed Curve A. If this analysis is correct it may be that for some reason the part of the total effect represented by Curve B was negligible in the specimen studied by Heaps. In view of the polymorphic character of iron this is not improbable. This would leave the curve C which corresponds to his observations. If such a splitting up of the effects into two parts is allowable it may be that there is still a proportionality between the change of resistance and one of the terms entering into the observed change of length and thermoelectromotive force. This analysis is the more probable in view of the effect of tension on the change of length and on the change of resistance. This effect of tension might be interpreted as decreasing that part of the effect represented by Curve B and leaving the second part essentially unchanged. When the tension was made large enough, a reversal of the change would then follow for sufficiently large magnetic fields. It would also follow that the larger the tension the smaller the magnetic field necessary to reverse the effect. If the tension were made large enough to render the first part of the effect represented by Curve B negligible in comparison with the second part represented by Curve C, the change of length and the change of thermoelectromotive force would always have the same sign and might be represented by the observed curves as found for large values of the tension.

In Figs. 4, 5, 6, 7 and 8 are given curves showing the change in the thermoelectromotive force as a function of the magnetic field for six alloys of iron and copper and three alloys of iron and nickel. All of these curves except those for the alloy containing 93 per cent. iron and 7 per cent. nickel and the alloy containing 88.7 per cent. iron and 11.3 per cent. nickel have the characteristics of the corresponding curves for pure iron. The addition of copper to iron changes the magnitude of the effect of a given longitudinal magnetic field on the thermoelectric power but in other respects the behavior of the alloys is very similar to the behavior of the iron. The direction of the thermoelectromotive force and also the direction of its change in the magnetic field is the same in these alloys as in pure iron. The addition of copper to iron at first increases the effect of the longitudinal magnetic field on the thermoelectromotive force. After the alloy contains 1.5 per cent. copper a further increase in the concentration of copper decreases the change in thermoelectromotive force.

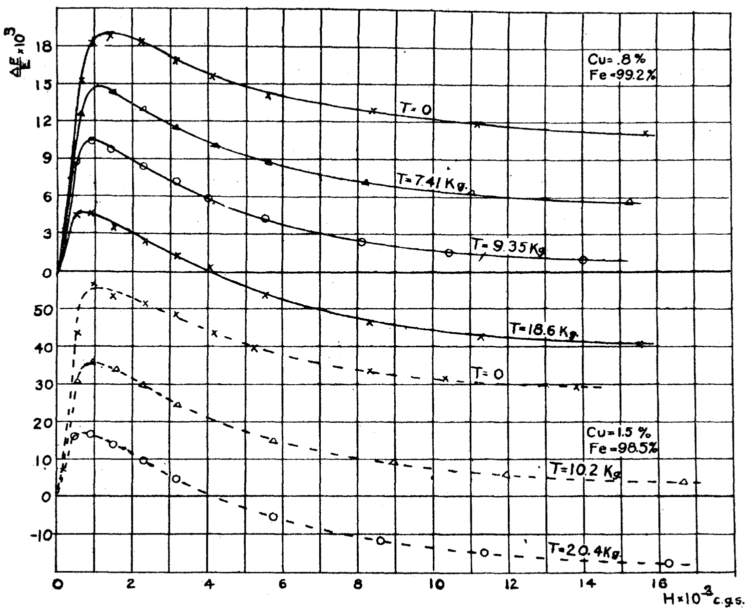

Cu=.8%
Fe=99.2%
T=0
T=7.41 Kg.
T=9.35 Kg.
T=18.6 Kg.
T=0
Cu=1.5%
Fe=98.5%
T=10.2 Kg.
T=20.4 Kg.
H×10³ c.g.s.

Fig. 4.

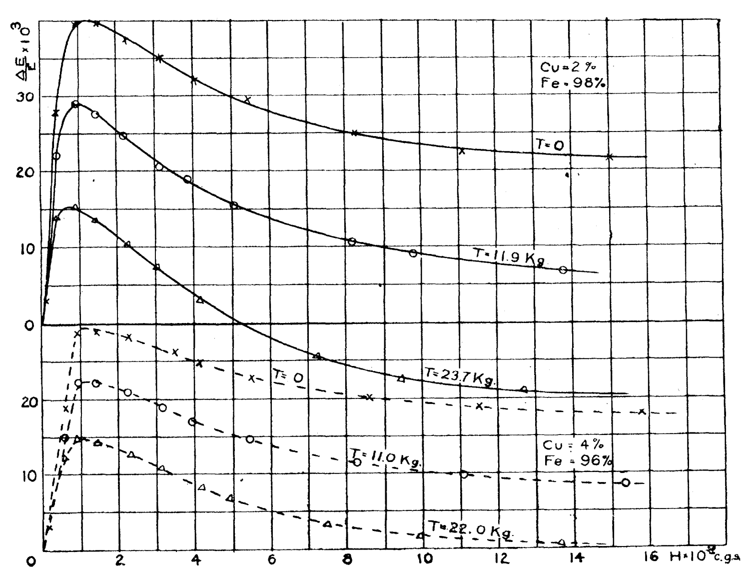

Cu=2%
Fe=98%
T=0
T=11.9 Kg.
T=23.7 Kg.
T=0
Cu=4%
Fe=96%
T=11.0 Kg.
T=22.0 Kg.
H×10³ c.g.s.

Fig. 5.

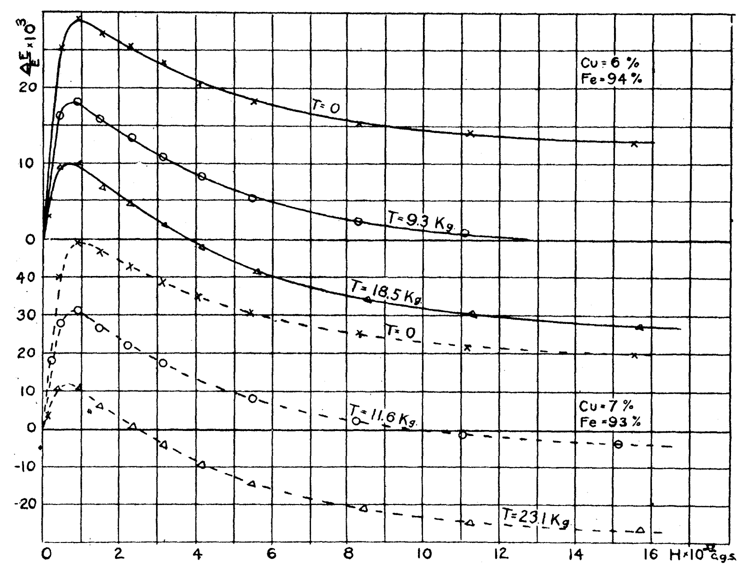

Cu = 6 %
Fe = 94 %
T = 0
T = 9.3 Kg
T = 18.5 Kg
T = 0
T = 11.6 Kg
Cu = 7 %
Fe = 93 %
T = 23.1 Kg

Fig. 6.

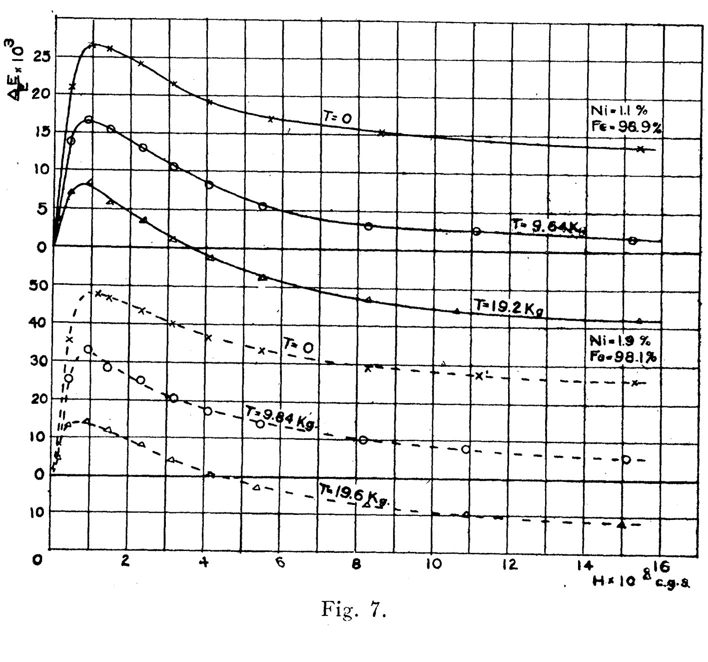

Ni = 1.1 %
Fe = 98.9 %
T = 0
T = 9.64 Kg
T = 19.2 Kg
Ni = 1.9 %
Fe = 98.1 %
T = 0
T = 9.64 Kg
T = 19.6 Kg

Fig. 7.

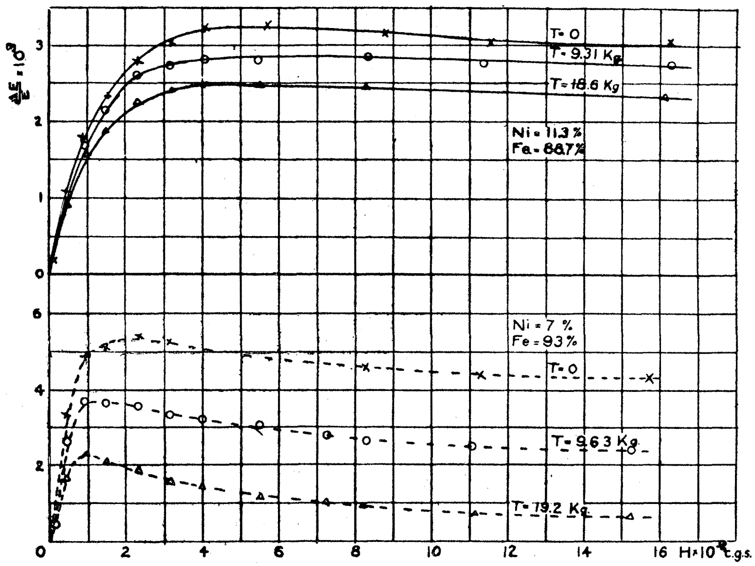
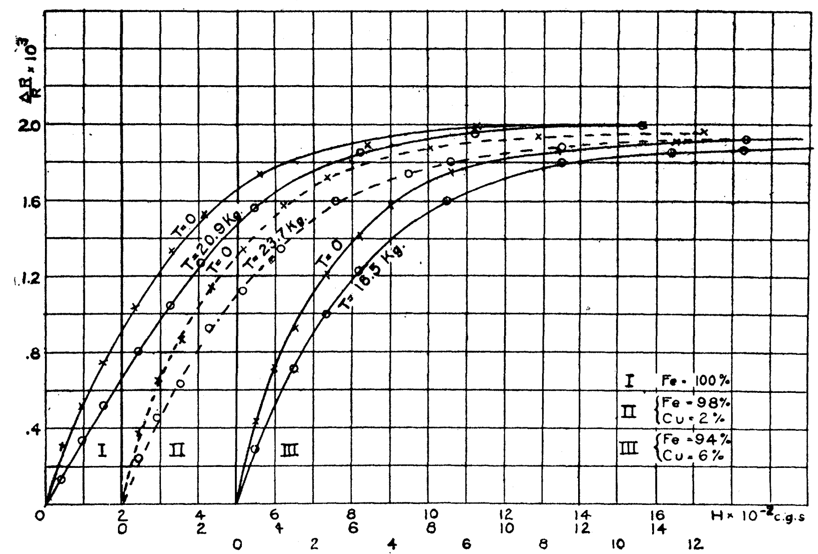


Fig. 8.

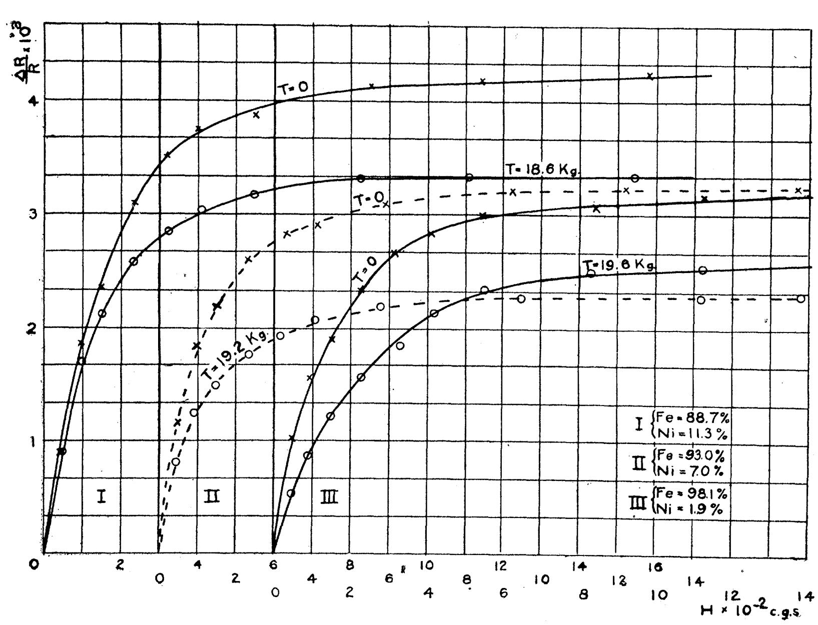
The addition of nickel to iron in small quantities causes an increase in the magnitude of the effect over that observed in pure iron. The direction of the thermoelectromotive force and the direction of its change in a magnetic field remain the same as in pure iron until the alloy contains about 7 per cent. nickel where a reversal of direction takes place in both. The alloy then begins to behave more like pure nickel. It still retains some of the characteristics of iron, passing through a maximum and showing a tendency to reverse its direction for sufficiently large tensions. An alloy containing 11.3 per cent. nickel and 88.7 per cent. iron shows more clearly the characteristics of nickel. The effect passes through a maximum as in the other sets of curves but the decrease after the maximum is passed is very gradual. The application of tension causes a decrease in the magnitude of the effect for all values of the magnetic field while in nickel it caused a decrease for low fields and an increase for large fields. The reversal of direction obtained in the preceding cases can not be realized in these alloys.

The longitudinal change of resistance in two of these copper-iron alloys has been represented in Fig. 9 and the observations on the nickel-iron alloys in Fig. 10. In each case the application of tension decreases the change of resistance. The change of resistance when the specimen is completely magnetized is somewhat smaller in those alloys which contain the greater percentage of copper. On the other hand the initial value of this change of resistance in pure iron for low magnetic fields is somewhat



T=0
T=20.9 Kg.
T=0
T=23.7 Kg.
T=0
T=18.5 Kg.
I Fe = 100%
II {Fe = 98% Cu = 2%
III {Fe = 94% Cu = 6%
H × 10^-2 c.g.s

Fig. 9.



T=0
T=18.6 Kg.
T=0
T=0
T=19.6 Kg.
T=19.2 Kg.
I {Fe = 88.7% Ni = 11.3%
II {Fe = 93.0% Ni = 7.0%
III {Fe = 98.1% Ni = 1.9%
H × 10^-2 c.g.s.

Fig. 10.

less than it is in the alloys containing copper. From Fig. 10 it is seen that the addition of nickel to iron increases the change of resistance produced by the magnetic field. It is also seen that the effect of tension is greatest where the amount of nickel is largest.

The upper curve of Fig. 11 shows the Hall constant as a function of the

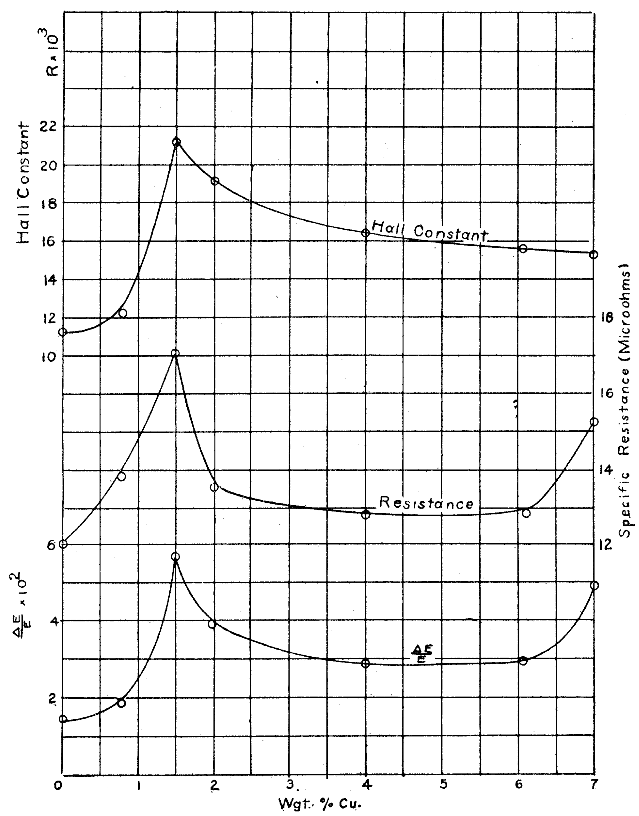


Fig. 11.

concentration of copper. This curve is taken from a former paper by the author.[1] The middle curve represents the specific resistance of these alloys. These resistances were determined by Burgess and Aston.[2] In the lower curve the fractional change in the thermoelectromotive force has been plotted against the concentration of the copper in the alloys. These changes in thermoelectromotive forces are those produced by a magnetic field of 98 gauss when the wire was not under tension. The similarity between these curves is quite evident. They have essentially

[1] Smith, PHYS. REV. (2), 17, 23, 1921.

[2] Burgess and Aston, Met. and Chem. Eng., 8, 79, 1910.

the same characteristics. There is a cusp in each curve where the alloy contains 1.5 per cent. copper. This interrelation for which there seems to be no satisfactory explanation indicates a dependence of all of these effects on some common property of the metals and alloys.

Discussion of Results.—The sources which may be thought of as operating to produce these changes of length, resistance and thermo-electromotive force are changes in the mean free path of the electron, in the number of electrons, in the amplitude of vibration of the atoms and in their frequency of vibration. The change in the mean free path of the electrons would arise from the molecular rearrangement and also from the change in path produced by the action of the magnetic field on the electrons. From this point of view the molecular rearrangement with its accompanying changes in the electric and magnetic forces would be entirely responsible for the change of length and a parallelism between the change of length and the change of resistance would be expected only when the influence of the molecular rearrangement on the mean free path is large in comparison with the effect of the magnetic field on the mean free path.

The application of tension might be expected to decrease the effect of the magnetic field on molecular rearrangement and so decrease the change of resistance and change of length arising out of molecular rearrangement. Since it has been seen that the observed effect in iron and in the iron-copper alloys may be regarded as made up of two parts and that one of these parts seems to be nearly wiped out by sufficiently large tensions it may be that part of the total effect represented by Curve A (Fig. 2) arises out of molecular rearrangement produced by the magnetic field. In view of the fact that this part of the effect is missing in nickel it would then be necessary to conclude from this point of view that molecular rearrangement gives rise to a small part of the effect in nickel.

Assuming that the number of free electrons is not changed by the action of the magnetic field Heaps[1] finds on the basis of the gas-free electron theory a proportionality between the fractional change of resistance and the fractional change of length in a longitudinal magnetic field. He thus arrives at the relation,

$$\frac{\Delta R}{R} = -\frac{\Delta\lambda}{\lambda} = -C\frac{\Delta l}{l},$$

where ΔR is change of resistance,

λ and $\Delta\lambda$ are mean free path and change of mean free path respectively,

l and Δl are length and change of length respectively.

[1] Heaps, Phys. Rev. (2), 6, 34, 1915.

Here it is seen that an increase in resistance is associated with a decrease in mean free path and a corresponding decrease in length.

If one holds to the constancy of the number of free electrons in the magnetic field it is not possible to explain the parallelism between the change of length, change of resistance and change of thermoelectromotive force on the basis of the gas-free electron theory. If, however, the number of free electrons is a function of the magnetic field and not the same function at different temperatures then the application of the magnetic field might set up a thermoelectromotive force between the ends of the wire. On the basis of these experiments showing the change in the thermoelectromotive force in a magnetic field it seems impossible to accept the assumption of Heaps that the number of free electrons is independent of the magnetic field.

It is of interest to consider these observations in connection with the gap theory of electric conduction developed by Bridgman.[1] From the point of view of this theory it is considered that the electrons pass without resistance through the atom and that the vibrations of the atoms determine the chance that an electron may pass from one atom to the next. This chance is a function of the amplitude of atomic vibration and of the distance from atom to atom. The greater the mean distance between atomic centers the greater the difficulty which the electron encounters in jumping the gap. It is, however, assumed that when the atoms are at rest the electrons encounter no resistance in passing across the gap provided the separation of atomic centers is not too great. If the mean distance between the atomic centers alone determines the probability that an electron pass from atom to atom, an elongation produced by the magnetic field would be associated with an increase in resistance, since the greater the distance between the atoms the greater the resistance of the metal. But in the case of nickel and possibly in the case of iron it has been seen that a contraction has been accompanied by an increase in resistance. It would, therefore, be necessary to conclude that the amplitude of vibration of the atoms is the controlling factor in determining these changes. The vibrations of the atoms might easily be considered different in the magnetic field from their vibrations in the absence of the field. Now the magnetic field produces an increase of resistance and Bridgman finds that the resistance is proportional to the square of the amplitude of vibration. Since the resistance is increased by the magnetic field it would follow from this theory that the amplitude of vibration has been increased by the magnetic field. Since with this increase in resistance there has been found to be associated a decrease in length and therefore a decrease in the distance between atomic centers we are

[1] Bridgman, PHYS. REV., N.S., 17, 161, 1921.

forced to conclude that the amplitude of vibration is greatest where the distance between the atoms is least. This does not seem to be a very reasonable conclusion unless the considerations introduced by Bridgman to explain the anomalous behavior of bismuth and antimony under pressure be carried over to the explanation of this difficulty. Accepting the assumptions of Grüneisen, Bridgman concludes that in these cases it may be possible to have an increasing amplitude of vibration with an increasing pressure and therefore an increase in resistance. The same reasoning would account for the fact that a contraction in the magnetic field is associated with an increase of resistance. This method of reasoning on the whole does not seem very satisfactory and it is necessary to conclude that the gap theory of electric conduction does not give a very satisfactory explanation of the fact that a decrease in length accompanies an increase in resistance in the magnetic field. In its present development this theory does not cover thermoelectric effects and has therefore no suggestion with respect to the relation between the change in thermoelectromotive forces and changes of resistance and length.

Another line of attack lies in assuming that the number of free electrons is a function of the frequency of the atom and that this frequency is changed by the application of tension and also by the magnetic field. The magnetic field produces a change in the orientation of the molecules and probably a change in the electric and magnetic forces acting in the interstices between the atoms. An elongation accompanying magnetization would increase the distance between the atoms and consequently decrease the electric and magnetic forces operating in the vacant spaces between the atoms. This decrease in the electric and magnetic forces would also produce a decrease in the frequency of vibration of the atom. If it be assumed, in agreement with March,[1] that an increase in the frequency causes a decrease in the number of free electrons, a contraction caused by the longitudinal magnetic field will be accompanied by an increase of resistance. This result is in agreement with the observations on nickel. This point of view would also offer a possible explanation of the change in thermoelectromotive force. When there is a change in the number of free electrons due to an elongation or a contraction of the metal in a magnetic field there would be a change in the concentration of the electrons. Since the wire is unequally heated this change in concentration might not be the same at the hot and the cold junctions. Hence thermoelectromotive forces would be set up. Their direction would depend on whether the magnetic field produced greater or less changes in the concentration as the temperature is increased.

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[1] March, Ann. d. Phys. 49, 710, 1916.