MAGNETOSTRICTION AND MAGNETOELECTRIC EFFECTS IN IRON, NICKEL AND COBALT

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Abstract

Magnetostriction effects in pure cobalt and in iron and nickel.—Various properties of the same sample of very pure cobalt wire (Co 99.73 per cent) annealed at 1100°C were determined and compared with those of Armco iron and commercially pure nickel. (1) *Wiedemann effect.* As found by Pidgeon, Co is intermediate between Fe and Ni, the twist for 6 amp./mm^2 decreasing to a minimum of 21 sec./cm for a field of 50 gauss. (2) *Joule effect* in longitudinal field for Co is also intermediate between Fe and Ni, $\Delta L/L$ decreasing steadily to -20×10^{-6} for 1000 gauss. For Fe, as has usually been found, the effect was positive only up to 250 gauss.

Magnetoelectric effects in pure cobalt and in iron and nickel.—(1) *Change of thermal e.m.f.* in longitudinal field. $\Delta E/E$ was positive for Fe, reaching a maximum of .021 for 110 gauss; for Ni, it was negative, increasing to $-.026$ for 1000 gauss; for Co, it was intermediate, reaching a maximum of only 5×10^{-4} and being negative above 300 gauss. The effect of loading Fe and Ni was to lower the curves considerably in the negative direction; for Co, the effect was less. (2) *Change of resistance* in longitudinal field. For Fe, $\Delta R/R$ increased to a constant value 2×10^{-3} for $H>800$ gauss; for Ni, it increased rapidly to a steady value 14.8×10^{-3} for $H>400$ gauss; for Co, the values were intermediate, increasing steadily to 4×10^{-3} for 1000 gauss.

$\mathbf{B}$ECAUSE of the importance of magnetostrictive and magnetoelectric effects in theories of magnetism, it is desirable that all these effects be studied carefully in the same specimen. The importance of such observations has already been pointed out by Williams[1] who emphasizes the fact that differences in purity and in the previous history of the specimens makes the coördination of the results of various observers difficult. The disagreement in this respect is illustrated by the work of Heaps,[2] who found that a longitudinal magnetic field produces a contraction in iron for all values of the magnetic field, but all other observers, except in the case of one determination by Bidwell, found an elongation in weak fields and a contraction in strong fields. Unfortunately, no analysis was given of the specimen used by Heaps.

These effects have received comparatively little attention in the case of cobalt, largely because of the difficulty of securing suitable specimens.

[1] Williams, Phys. Rev. **10**, 129, 1917.
[2] Heaps, Phys. Rev. **6**, 34, 1915.

Among those who have studied cobalt are Honda and Nagaoka,[3] Goldhammer,[4] Bidwell[5] and Pidgeon.[6] In most of these cases mention is made of the fact that the annealing was imperfect and the specimen impure. Fortunately a careful study of cobalt has been made for the Bureau of Mines in Canada under the direction of Eugene Haanel at the School of Mining at Queen's University. This study resulted in the production of a very pure metal which could be drawn into the form of wires. A specimen of this wire previously used by Pidgeon was available for this work. Its analysis was as follows: $Co = 99.73$, $Fe = .14$, $Ni = .00$, $S = .01$, $C = .09$, and $Si = .02$ per cent.

Neither the specimen of iron nor that of nickel has been analyzed as, in view of the immense amount of work done on iron and nickel speci- mens in the past, it did not seem necessary. The former was pure Armco; the latter was labelled pure nickel by the Driver Harris Co.

The dimensions of the specimens were:

	Length	Diameter
Cobalt	22.3 cm	0.88 mm
Nickel	17.0 cm	1.25 mm
Iron	25.0 cm	1.02 mm

The cobalt was annealed at 1100°C in a chromel resistance furnace for two hours, with hydrogen flowing through the furnace. The specimen was then slowly cooled to room temperature and found to be fairly flexible. Annealing at a temperature lower than 1100° C left the metal quite stiff. The iron and nickel specimens were annealed at 950°C for two hours and then cooled slowly. At the end of this treatment they were soft and flexible.

THE WIEDEMANN EFFECT

The solenoid used in the work on the Wiedemann effect in iron was one built at the Carnegie Institute of Technology by Grondahl.[7] It had a calculated constant of 122.5 gauss per ampere. Since it was wound with No. 8 wire, large currents could be used for short intervals without heating. For the remainder of the work a second coil was wound with No. 12 wire. Its constant, carefully determined by two independent methods, was 110 gauss per ampere. The solenoids were sufficiently long so that the fields were uniform to about two per cent over a length of 25 cm in the center. A layer of fine wire wound on the outside of the coil

[3] Honda and Nagaoka, Phil. Mag. **4**, 45, 1902.
[4] Goldhammer, Wied. Ann. **31**, 360, 1887.
[5] Bidwell, Roy. Soc. Proc. **48**, 469, 1890.
[6] Pidgeon, Phys. Rev. **13**, 209, 1919.
[7] Grondahl, Phys. Rev. **4**, 325, 1914.

served to compensate the vertical component of the earth's magnetic field. Since the solenoid was always used in the vertical position no compensation was made for the horizontal component.

For work on the Wiedemann effect the specimen was supported between two brass rods and was surrounded by a cooling tube through which water ran continuously. The specimen was fixed to a bracket on a pillar separate from the building. Even with this precaution, the vibrations of the building caused trouble especially in the case of cobalt.

The method for the measurement of the Wiedemann effect was that used by Pidgeon.[6] It was necessary to compensate carefully for the earth's magnetic field, especially in the case of nickel. Pidgeon found that a small twist resulted when he used only one of the two fields. This was nearly all eliminated by careful compensation. The small residue may be due to aeolotropy in the material.

In the case of iron nothing was found at low fields that was not already well known, but on carrying the fields to high values it was found that

TABLE I

Soft iron I_c 2.7 amp./mm²		Nickel I_c 2.38 amp./mm²		Cobalt I_c 6.00 amp./mm²	
$H(gauss)$	$\theta(sec./cm)$	$H(gauss)$	$\theta(sec./cm)$	$H(gauss)$	$\theta(sec./cm)$
2.8	5.4	3.2	41.7	4.3	1.3
4.0	7.7	4.0	55.5	8.5	3.8
5.2	10.2	4.8	58.5	19.3	9.0
5.8	14.0	5.6	66.1	35.4	17.7
6.9	17.1	6.4	76.0	50.2	20.5
8.7	21.0	7.2	76.5	72.0	17.0
11.0	25.0	8.0	86.0	85.4	13.8
15.2	26.7	10.4	86.0	105.2	10.2
25.5	24.4	11.2	90.5	168.2	5.2
63.5	16.6	16.0	89.5	240.3	3.1
113.2	5.5	22.7	79.5	400.2	2.0
158.0	3.02	36.0	66.3	570.2	1.9
207.2	1.72	72.0	36.5	860.3	1.9
253.0	1.16	101.8	28.5	1230.5	1.8
300.5	0.29	140.0	20.5		
335.2	− .75	168.2	18.2		
382.0	−1.16	207.0	14.6		
430.0	−1.46	233.3	13.2		
464.3	−1.56	273.5	11.9		
497.6	−1.86	327.8	9.9		
695.0	−2.6	344.2	7.3		
1160.4	−4.3	815.4	3.3		
2080.2	−5.8	1230.0	0.66		
		2080	0.5		

NOTE. The negative sign in the case of iron means negative twist. In the case of nickel and cobalt all the twists are in the negative direction. Fewer readings were taken on cobalt owing to the danger of heating by the high current used and a consequent change of structure. The data taken by Pidgeon on the same specimen seem to agree very well with the results of the author, so that only a limited number are given in the paper.

the twist in the opposite direction, which we shall call negative,* did not tend to return to the axis of zero twist as found by Pidgeon, but continued to increase negatively up to the highest fields used, about 2500 gauss. In both Fig. I and Table I, I_c is the current flowing in the specimen.

A sample of electrolytic iron, furnished through the kindness of Mr. Hopkins of the Westinghouse Mfg. Co., was given the same heat treatment as the other sample of iron, and was found to have the same general characteristics as the Armco iron. Twists in it (Fig. 2) were very steady and easily reproduced.

In nickel (Fig. 1) the usual type of twist was found. It is negative for small fields, reaches a maximum and then approaches the axis of zero twist for high fields. In the largest fields used the twist was very nearly zero.
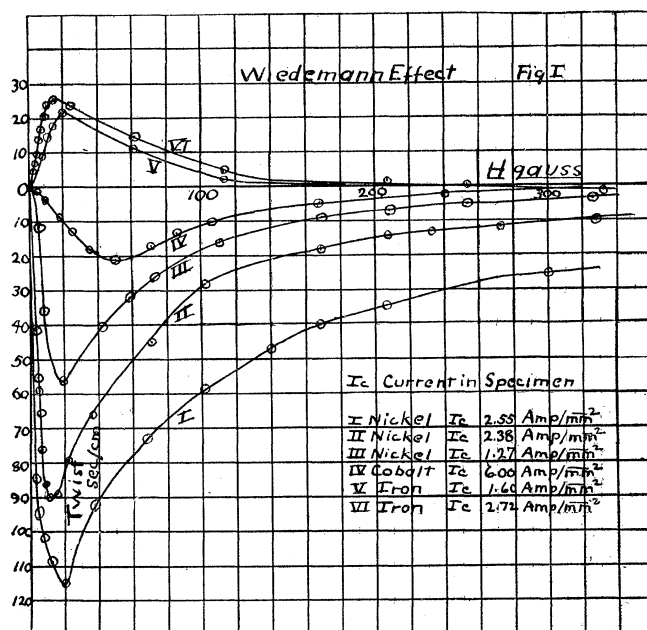
Fig. 1. Wiedemann effect.

The results for cobalt (Fig. 1) confirmed those obtained by Pidgeon on the same specimen. They are consistently intermediate between iron and nickel. This suggested the investigation of other effects to see whether this was always true.

* The convention of positive twist is that for iron at low fields when the lower end of the solenoid is a north pole, and the current is flowing from top to bottom of the wire.

THE JOULE EFFECT

This effect, the change in length with magnetic field, has received much attention in the case of iron and nickel. The results obtained for cobalt by various observers have not been consistent. Bidwell found that cobalt first decreases in length in low magnetic fields, then reaches a mini-
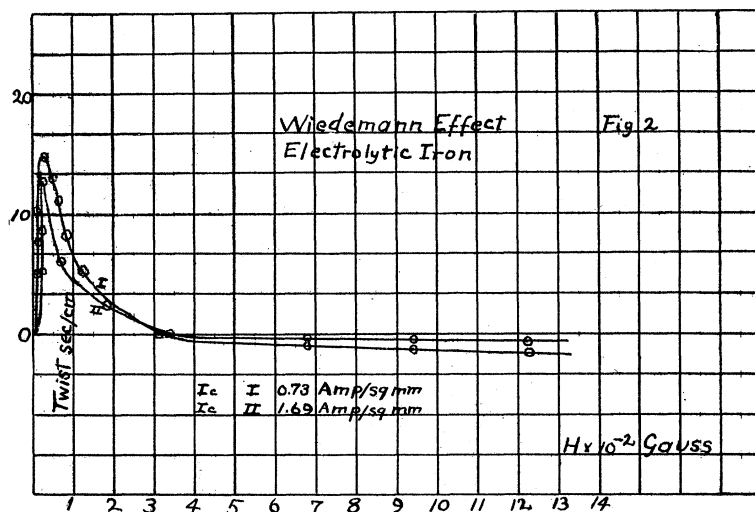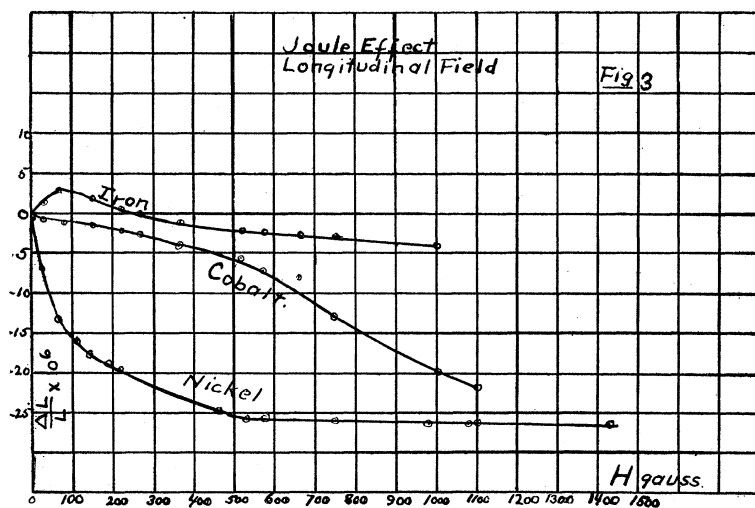

Fig. 2.   Wiedemann effect in electrolytic iron.

Fig. 3.   Joule effect with longitudinal field.

mum and finally increases in length as higher fields are reached. Honda found a continual decrease in length.

Two methods were used to measure this effect. One was the bifilar method described by Grondahl. The other was an optical lever method which consisted in the combination of a first class lever with an optical lever. The distance between the front and back legs of the optical lever was 3 mm, and the telescope and scale were placed 4 meters away. This combination gave a magnification of 30,150. An attempt was made to carry this magnification higher but vibrations interfered.

The results reported here (Fig. 3) show that in cobalt there is a continual decrease in length. It is small for low fields, but reaches no maximum in the fields used in these experiments. Disregarding the small increase in length in iron for low fields, the Joule effect is always negative; with cobalt it is intermediate between iron and nickel. A careful study of the change in length in cobalt for magnetic fields less than 100 gauss was made, to see if there might be a small increase in length at low fields. Nothing of this character was found with the magnification used.

The usual initial increase in length was found consistently in iron. The result obtained by Heaps—a contraction for all magnetic fields— was not observed.

CHANGE OF THERMAL ELECTROMOTIVE FORCE

In the determination of the change of thermal electromotive force in a longitudinal magnetic field a Wolff potentiometer was used with a Leeds and Northrup high sensitivity galvanometer. The accuracy of the potentiometer was checked frequently with a Weston cell. The sensitivity of the galvanometer at 3 meters was 6.07 mm per microvolt. The junctions which were formed by soldering the ends of the specimens to copper wires, were kept in melting ice and steam. It was found difficult to keep the temperature of the ice junction constant but by drawing off the water frequently, the zero of the galvanometer could be maintained for several minutes.

This change of thermal electromotive force in pure ductile cobalt was of added interest because Smith[8] has studied it in iron, nickel and a number of alloys, and Grondahl and Karrer[9] had observed this change in a bar of cast cobalt. The results (Fig. 4) show an increase to a maximum for iron in low fields. This is followed by a decrease in high fields. It is unfortunate that this effect was not studied by Heaps, as there is a

[8] Smith, Phys. Rev. 19, 285, 1922.
[9] Grondahl and Karrer, Phys. Rev. 33, 531, 1911.

possibility that the sample used by him might have shown a continual decrease. Nickel increases in the opposite direction and seems to approach a maximum. These results are very similar to those obtained by Smith. Cobalt shows a small change in low fields in the direction of iron. In higher fields the change is in the direction of nickel as one should expect from the direction of the Peltier effect in a copper cobalt junction. The curve of Grondahl and Karrer does not show the initial change. Cobalt is again intermediate between iron and nickel.
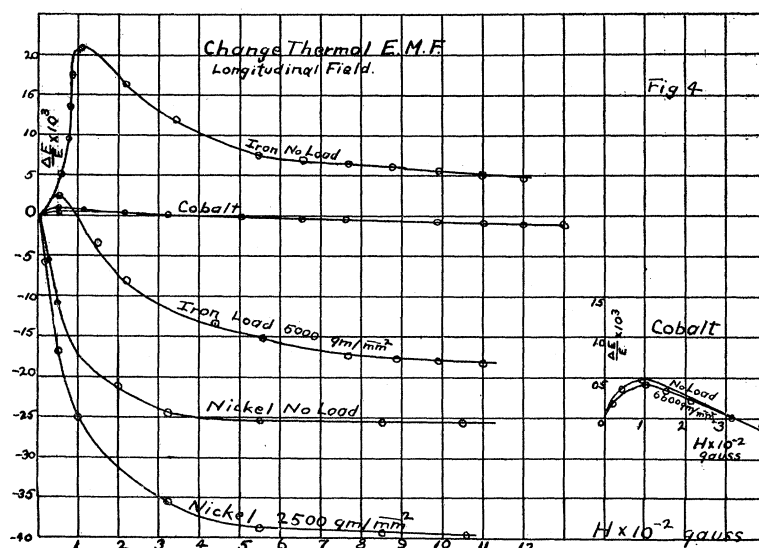

Fig. 4. Change of thermal e. m. f. with longitudinal field.

In this connection the effect of loading the specimen with weights was tested. The results are in agreement with those found by Smith. Cobalt behaves like iron in this respect. For the small loading used in the case of cobalt the curves did not vary much at high fields. This deserves further study as small loads were used in order to avoid risk of setting up any internal changes in the structure of the specimen.

CHANGE OF RESISTANCE

The change of resistance in a longitudinal magnetic field was measured on a Kelvin double bridge with a Leeds and Northrup high sensitivity galvanometer. A change of 1×10^{-5} ohm could be detected. The bridge was equipped with a sliding contact for a null method which was found very satisfactory. A deflection method was tried and the results were the same in both cases. To correct for possible thermal electromotive

forces set up at the contact, the current was reversed in the bridge for each reading. The mean of the two readings differed little from either reading. Because the resistance of the specimens never exceeded 0.04 ohm there was small danger of change of resistance due to the heating of the specimen. Nevertheless water at constant temperature was kept constantly running through the cooling tube and the readings were taken as rapidly as possible to avoid error. It was evident that very little change took place as the initial resistance remained practically constant during the series of runs.
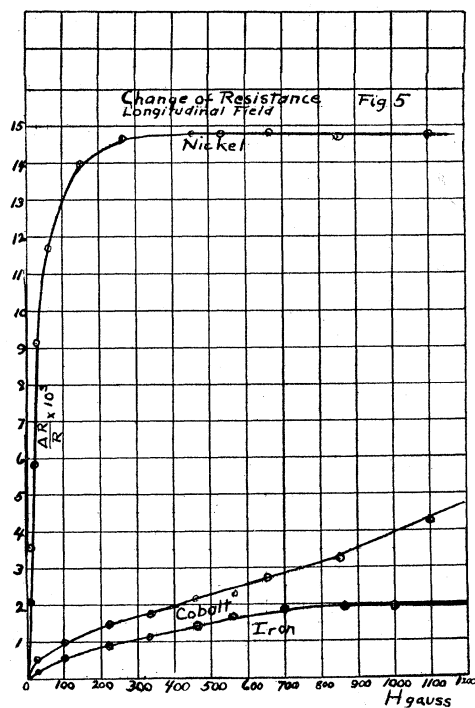

Fig. 5. Change of resistance with longitudinal field.

The results for iron and nickel are in agreement with those of other observers. In the case of cobalt (Fig. 5) an increase of resistance intermediate between those of iron and nickel was found. In each case, then, the effect for cobalt is intermediate between those for iron and nickel, in agreement with the order of the atomic numbers of the three metals.

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