The Variation with Magnetic Field and Temperature of the Thermoelectric Properties of Ferromagnetics*

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It was first shown by Sir Wm. Thomson that a thermocouple may be composed entirely of iron or nickel provided part is in a magnetic field and part not. A survey of the work previously done on this subject and an experimental investigation of a more extended nature than any heretofore have been attempted in order to clear up existing confusion and render the subject more available to theoretical interpretation. Measurements on iron, nickel, cobalt and permalloy from room temperature to above the Curie point indicate that the e.m.f. produced by a magnetic field in these thermocouples is conditioned by (1) the crystal structure and (2) the change in direction of the resulting spins or intrinsic magnetization in separate crystal regions, and that this effect is related to the change in length on magnetization.

INTRODUCTION

IT was first shown by Sir Wm. Thomson[1] in 1856 that a thermocouple may be constructed entirely of iron or of nickel provided the two parts are in different states of magnetization. Numerous investigations have since been made of the effect with conflicting results. Thomson,[1] Battelli[2] and Broili[3] found the e.m.f. opposite for iron and nickel, but Strouhal and Barus,[4] Chassagny,[5] Bidwell,[6] Cohen,[7] Grondahl and Karrer,[8] Bordoni,[9] T'Ao and Band,[10] Ross[11] and finally Perrier and Kousmine[12] have found the e.m.f. positive, i.e., from magnetized to unmagnetized metal at the cold junction, in both cases. (Here and elsewhere reference is to a longitudinal field; a transverse field generally gives the opposite direction to the effect.) In the case of iron the e.m.f. was sometimes observed to decrease for strong magnetic fields and Bidwell,[6] Houllevigue,[13] Rhoads,[14] Smith[15] and Broili[3] actually obtained a reversal, although Smith applied tension and Broili "recrystallized" his specimen. This decrease or reversal in strong fields suggested to some[6, 15, 16] a connection with the similar change in length on magnetization, but in the case of cobalt[6] and Heusler alloys[8] no relationship was found. Others[15, 17, 18] have postulated a connection between this effect and the change of resistance in a magnetic field, but the analogy is close only for nickel. Finally the state of confusion in regard to this effect has recently been exemplified by Gerlach[17] and by Ross[11] and Williams[19] who have reported a "new effect" which is in reality only that discovered by Thomson.

In view of the present confused state of the subject of Thomson's thermomagnetic effect the present attempt has been made first to review all the previous work done, and second, to repeat experimental measurements. In previous work

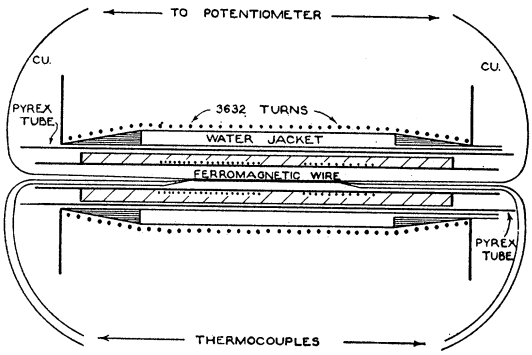

FIG. 1. Cross section of furnace and solenoid.

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the effect has been studied with only one or two substances at a time and often without uniform magnetization or a wide temperature range, whereas in this attempt the effect has been studied by comparison of the magnetized metal in a uniform field with the same metal unmagnetized, from ordinary temperatures to above the Curie points, under identical conditions for each of the metals used and for as many different substances as possible in order that the resulting data might be more available for interpretation.

Experimental Method

Wires of iron, nickel and cobalt were secured from Baker and Co.; they had been prepared by the Taylor process and were 99.9 percent pure or better by analyses. The iron and nickel were 0.2 cm in diameter and approximately 14 cm long, while the cobalt was 0.025 cm in diameter and 10 cm long. The permalloy wires, kindly donated by the Bell Telephone Laboratories, contained 78.5 percent nickel and were 0.05 cm in diameter and 10 cm long.

To demagnetize the specimens the iron wires were heated to 800°C and two nickel wires to 450°C and allowed to cool slowly in vacuum. One nickel wire was simply demagnetized by the method of reversals but the experimental results were the same for this wire as for the other two nickel wires which were heated above the Curie point, hence thereafter all specimens were demagnetized by reversals. All specimens were eventually heated a little above their Curie points during the course of the measurements, but their properties were not affected appreciably.

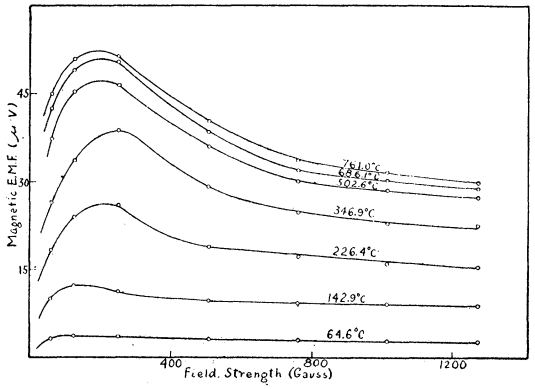

Fig. 2. Iron with cold junction temperature of 32.0°C.

In order to compare magnetized with unmagnetized materials the thermal e.m.f. of each was measured against copper, first for the demagnetized state and then when subjected to uniform longitudinal fields up to 1300 gauss. Thus the specimens could be held entirely in a uniform field and the transition regions relegated to the copper part of the circuit. The experimental arrangement is shown in Fig. 1. The specimen was welded to copper leads and copper-constantan thermocouples held in contact with the junctions by wrapping with fine copper wire. The specimen was then placed in an alundum tube carrying two noninductive windings for controlling the temperature of each end. The tube was covered with an asbestos coat and was all contained in a Pyrex tube which was sealed at the ends and evacuated, thus preventing oxidation and reducing heat conduction. This was all placed inside a water-cooled solenoid with tapered ends. A search coil showed the field produced constant within one percent over the middle third, which contained the specimen. A null method using an L. and N. type K potentiometer for measuring the e.m.f.'s was sensitive to 1/10 microvolt. The temperatures of the junctions were maintained constant to 1/300°C during the interval in which measurements were made. It was necessary to insulate each part of the apparatus by using sulphur blocks for supports in order to eliminate electrical leaks and galvanometer drift.

Results and Conclusions

Although two or three wires of each material were tested the results for the specimens of the same metal did not differ appreciably. In Figs. 2, 3, 4 and 5 is shown the change in the normal thermal e.m.f. against copper on application of magnetic fields up to 1300 gauss for iron, nickel, cobalt and permalloy, respectively. This is called ΔE or the "magnetic e.m.f." and also represents the e.m.f. of each metal magnetized against the same metal unmagnetized. In every case ΔE was positive except for cobalt when it was slightly negative unless the hot junction, T_2, was above 350°–400°C when it again became positive. Remembering that the normal e.m.f. against

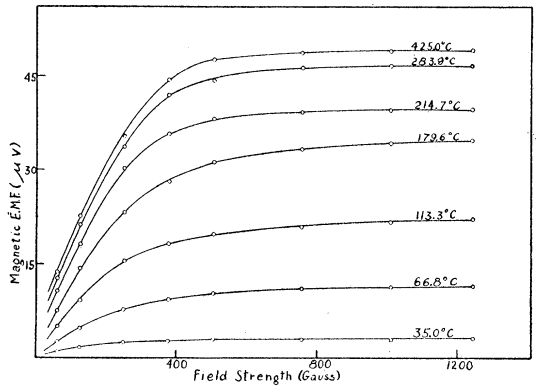

FIG. 3. Nickel with cold junction temperature of 22.5°C.

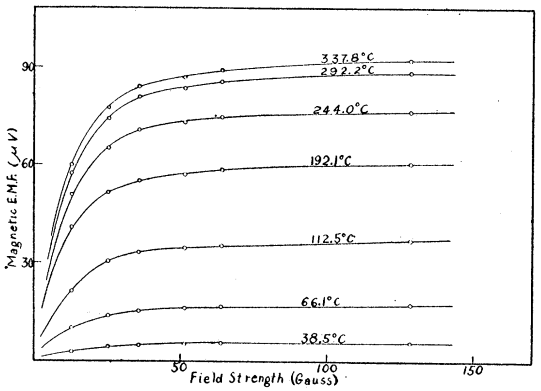

FIG. 5. Permalloy with cold junction temperature of 25.0°C.

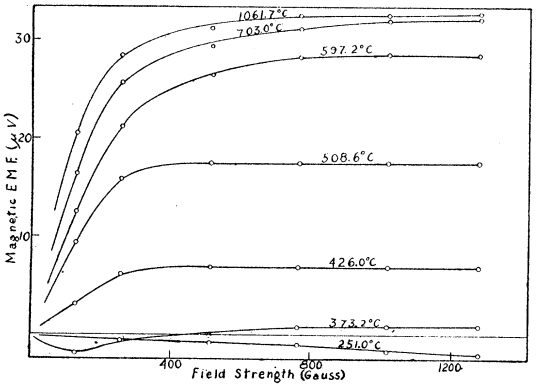

FIG. 4. Cobalt with cold junction temperature of 56.1°C.

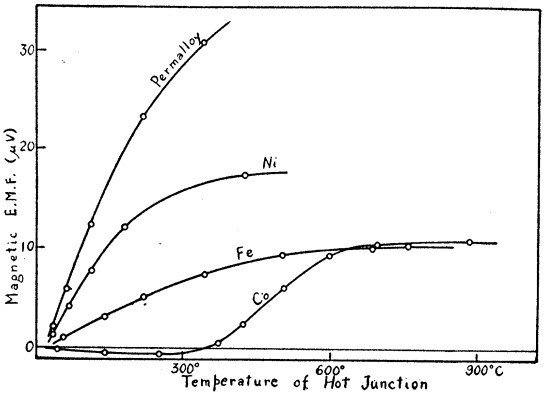

FIG. 6. Cold junction at 25°C, $H=1018$ gauss.

copper is negative for nickel, permalloy and cobalt, and for iron above about 470°C, it is seen that ΔE represents an actual decrease in the magnitude of the total e.m.f. against copper for nickel and permalloy, for cobalt above 350°–400°C and for iron above 470°C, otherwise ΔE represents an increase in the size of E.

In Fig. 6 is shown the variation of ΔE with the temperature of the hot junction, T_2, for a field of 1018 gauss. Each curve was carried above the Curie point except for cobalt and in every case saturation was attained as the Curie point was approached. This indicated the effect was truly a ferromagnetic one. It was also noted that the direction of the field made no difference provided it was longitudinal. Finally, although demagnetization was carried out for the data shown in the figures, it was found that the data could be nearly duplicated without demagnetization between readings, indicating that the specimens were magnetically very soft (the B *vs.* H curves were also actually found), as was also suggested by the failure of the effect to show any hysteresis with the field.

The data show similar behavior for nickel and permalloy, and for cobalt at higher temperatures; in each of these cases the crystal structure is the same, face-centered cubic. Iron, which is body-centered cubic, and cobalt below 400°C, when it is hexagonal, gave quite different results. The conclusion is that crystal structure is one of the factors governing the effect.

The curves for change of resistance with magnetic field are of the same type for all the four metals, and although similar to the ΔE curves for nickel, cobalt above 400°C and permalloy there is no analogy in the case of iron. This indicates no close relationship between these two effects.

The change in length on magnetization shows a

closer resemblance, the curves being very similar in shape and sign to those for ΔE except in the case of nickel where Δl is negative and ΔE positive. In the case of iron the analogy is very close, the Δl *vs.* H curves showing the type of maxima in Fig. 2. In the case of the change of length an explanation has been found by studying single crystals. For iron the (100) is the direction of easiest and the (111) of hardest magnetization, and Δl is always positive for the former and negative for the latter.[20] A polycrystalline specimen would therefore show the combined effects for single crystals magnetized parallel to (100) and (111) directions, respectively, the direction of easy magnetization predominating for low fields. The same explanation may be advanced for the ΔE curves. The following summarizes the picture: According to Weiss' and later theories a ferromagnetic substance is regarded as containing regions or "blocks" of the order of 10^5 atoms which are magnetized to saturation without an external field; on gradually increasing the external field the "blocks" are lined up parallel to that (100) direction in each crystal nearest that of H, thereby increasing l and E, the resistance, R, remaining unchanged; finally in strong fields the "blocks" must turn slowly from (100) directions into more exact parallelism with H or somewhat in (111) directions, thereby decreasing l and E and increasing R. A similar picture follows for the other metals. In the case of nickel Δl is of the same sign[21] and hence also ΔE for all directions and the (111) is the direction of easiest magnetization. It would appear that ΔE and Δl are both due to the same thing.

The above conclusions are in accord with those of Akulov[22] and Chramov and Lwowa,[23] who conclude that ΔE may be produced by magnetization or stretching and is conditioned by (1) crystal structure of specimen, (2) change of direction of resulting spins in separate crystal regions.

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The Relation Between the Electron Field Emission and the Work Function of Liquid Mercury

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The variation in the field necessary to initiate a vacuum discharge between a mercury cathode and a molybdenum anode and the accompanying variation in the work function of the cathode have been measured. The work function variations were obtained from measurements of the contact potential between the mercury and a platinum filament. The fields were applied by an impulse circuit, the time constant of the voltage wave being very short in order to prevent distortion of the mercury. The final results show a variation of the field with work function which, while in the same direction, is more pronounced than that forecast by the Fowler-Nordheim theory. For a change of work function of one volt the field required to initiate the discharge varied from 375 kv/cm to 575 kv/cm.

INTRODUCTION

NUMEROUS experiments[1] have been performed to study the relation between the field current and the field strengths involved. Several theories[2] have been proposed to forecast what this relation should be or to fit the experimentally found relation, the latest being that of Fowler and Nordheim. As a whole the results of various experiments on the problem have been capable, after making an assumption regarding the work function of the surface serving as cathode, of being fitted to an expression such as they have deduced.[3] The present experiments were carried out to investigate the relation con-

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