SOME PHYSICAL PROPERTIES OF NICKEL-IRON ALLOYS.

BY L. R. INGERSOLL AND OTHERS.[1]

SYNOPSIS.

The specific heats, thermal conductivities, thermoelectric powers, and specific resistances have been determined for a series of *iron-nickel alloys* of exceptional purity and definitely known composition.

The *specific heat* (25° to 100° C.) varies only slightly with change in composition, but gives, nevertheless, a well defined maximum at 35 per cent. nickel. The *thermal conductivity* (20° to 100° C.) on the other hand, shows a much larger variation. with a value for 35 per cent. nickel of only one fifth of that for either pure iron or pure nickel. The *thermoelectric power* (0° to 96° C.) against copper exhibits a marked minimum at 35 per cent. nickel with maxima at about 20 per cent. and 50 per cent. The *specific resistance* at 0° C. shows a marked maximum at 35 per cent. nickel, more than five times the value for either pure iron or pure nickel. The relative increase is not so great as the temperature is raised to 700° C. The temperature coefficient of resistance, considering the whole range (0° to 700° C.), is a minimum for the 35 per cent. nickel.

These facts are in general agreement with the anomalies in other properties shown by nickel-iron or nickel-steel of this composition and point to the formation of the definite compound Fe_2Ni.

WHILE nickel-iron and nickel-steel alloys have been very extensively investigated[2] as regards their mechanical, magnetic and similar characteristics of practical interest, other properties of equal importance to the physicist have been little studied. It is true that K. Honda[3] has measured the thermal (as well as the electrical) conductivities of a series of nickel steels, and W. Brown[4] the specific heats for a number of specimens containing up to 31 per cent. nickel, but no attempt has been made in the way of determining and correlating these and other physical properties for the same series of specimens.

In an extended research on the properties of alloys of iron with nickel and copper, carried out in the electrochemical laboratory of the University of Wisconsin some years ago, a considerable number of ferronickels were produced. These formed a graded series, of nickel content

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[1] The measurements for this work were carried out at various times by Messrs. O. F. Mussehl, D. L. Swartz, H. F. Smith, C. G. Thompson, M. A. Mahre and Misses J. F. Frederickson and D. R. Hubbard, working under the direction of Professor Mendenhall, Professor Terry or myself.

[2] Vide Bureau of Standards Circular No. 58 for a résumé of such work.

[3] Tohoku Univ. Sci. Reports, **7**, 59, 1918.

[4] Roy. Soc. Dublin, Trans., **9**, 6, 59, 1907.

varying from 1 to 90 per cent., and of such purity of material and definitely known composition as to afford a rather unusual opportunity for experimental studies of the sort described here. They were furnished through the kindness of Mr. James Aston, by whom, in connection with Professor C. F. Burgess, they had been made and their mechanical and electrical properties studied.[1] These showed unusual changes when the nickel content was between thirty and forty per cent.—in keeping with the remarkable properties of 35 per cent. nickel-steel, *e.g.*, invar. It seemed of importance, then, to determine if the same was true of certain other of their physical properties and accordingly their specific heats, thermal conductivities, thermoelectric powers and resistances as a function of temperature have been studied in this connection.

Table.

Alloy.	Per Cent. Nickel.	Specific Heat 25–100° C. $\left(\frac{\text{Cal.}}{\text{Gm.}}\right)$.	Thermal Conductivity 20–100 °C. (C. G. S. Units).	Thermoelectric Power (Against Copper) 0–96 °C. $\left(\frac{\text{Microvolts}}{\text{Deg. °C.}}\right)$.	Specific Resistance 20 °C. $\left(\frac{\text{Microhms}}{\text{Cm.}^3}\right)$.	Temperature Cofficient of Res. 0–100 °C.
Fe......	0	....	.1428	....	....	....
144E....	1.07	.1162	.1035	....	....	....
144F....	1.93	.1170	.1009	....	....	....
150J....	4.0	....	....	2.32	20.9	.0020
150L....	7.0	....	....	7.32	25.2	.0023
144J....	7.05	.1163	.0727	....	....	....
157D....	10.20	.1168	.0687	....	....	....
166A....	13.0	....	....	16.9	33.0	.0018
144M....	13.11	.1160	.0534	....	....	....
166B....	14.0	....	....	17.2	33.9	.0016
166E....	18.0	....	....	21.0	35.9	.00084
144P....	19.21	.1163	.0502	....	....	....
150S....	21.0	....	....	23.5	38.8	.0018
166G....	22.11	.1163	.0490	21.0	40.0	.0018
154S....	25.20	.1181	.0320	....	....	....
166I.....	26.40	....	....	16.7	35.9	.0016
166C....	28.42	.1191	.0278	....	....	....
166L....	35.09	.1228	.0262	9.79	92.0	.0011
166M ...	40.0	....	....	22.4	74.1	.0022
166N....	45.0	....	....	29.0	....	....
166O....	47.08	.1196	.0367	31.9	47.5	.0036
166Q....	75.06	.1181	.0691	....	....	....
173W ...	90.0	....	....	17.9	15.5	.0034
Ni......	100.0	.1168	.1402	....	....	....

Alloys.—The alloys had been prepared with the aid of a resistor furnace by melting[2] weighed amounts of iron and nickel in a magnesia crucible

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[1] Met. & Chem. Eng., **8**, 23, 1910.

[2] For a more detailed description of this process see Univ. of Wis. Bull. No. 346, Eng. Series, Vol. 6, No. 2, p. 6.

supported by a graphite jacket. The iron was obtained by a process of double electro-deposition and was 99.97 per cent. pure. The nickel was also electrolytic material of high purity. The resulting ingots, which weighed about 500 g. each, had been forged into rods and then machined into bars about 1 cm. in diameter. In the case of most of the specimens tested, the exact composition had been determined by chemical analysis, and the close agreement of the analytical results with the percentage of nickel added to the charge may be taken as evidence of the perfect alloying of the iron and nickel. The carbon content was estimated at considerably less than 0.10 per cent.

As will be noted on inspection of the table, the series of specimens on which the specific heat and conductivity measurements were made was not identical with that on which the other experiments were performed. While this is perhaps to be regretted, the fact that all these alloys were made in exactly the same way and of materials of the same purity, practically does away with any objection arising from this circumstance. It may be remarked that the specimens for which the nickel content in the table is given to two decimal places (*e.g.*, 22.11 per cent.) are those for which an exact analysis had been carried out. The composition of the others (*e.g.*, 13.0 per cent.) was determined from the amounts of materials used in forming the alloy and hence it is not so accurately known.

Specific Heat.—The specific heats were determined by means of a Joly steam calorimeter, using a delicate Sartorius balance. Before testing, samples of the alloy which weighed about 38 grams each were annealed by packing them in iron filings in an electric furnace and heating to 900° C. for over an hour, then cooling very gradually. The specimens were then carefully polished with various grades of emery paper. Three different sets of measurements were made, all of which gave results in excellent agreement. The mean values only are included in the table and plotted in Fig. 1.

The results are in good agreement with the measurements of Brown, already mentioned, although he did not investigate specimens with more than 31.4 per cent. nickel. The maximum in the curve at 35 per cent. nickel is very marked although the actual change in specific heat is small.

Thermal Conductivity.—This was determined by the well-known method of Gray.[1] The specimens used were those for which the specific heats had already been measured. They were between 5.1 and 6.7 cm. in length and of an average diameter of about .98 cm. To minimize losses,

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[1] Proc. Roy. Soc. London, **56**, 199, 1894.

the copper ball, to which the heat was conducted, was surrounded by a jacket through which flowed water at room temperature. The rod itself was jacketed with cotton wrapping. Curves were plotted of the temperature of the copper ball as a function of time and a tangent to these curves drawn at the point of room temperature enabled one to determine the rate at which heat was being conducted along the rod to the copper ball. Three determinations, in general showing good agreement, were made for each specimen and the average results are given in the table and plotted in Fig. 2. The conductivities of pure iron and pure nickel are taken from measurements of Jäger and Diesselhorst.[1]

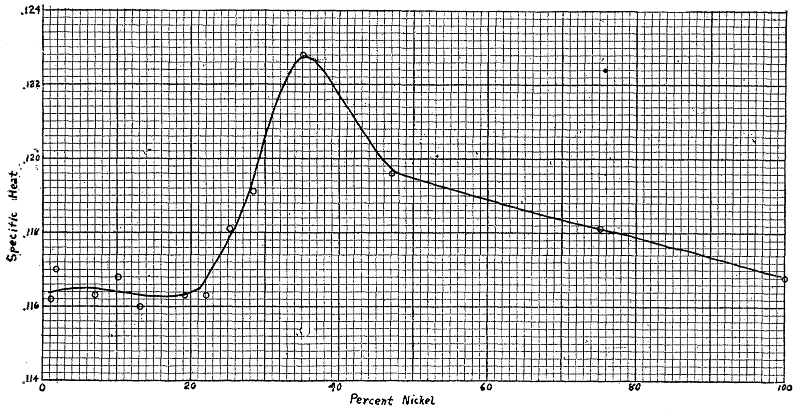

Fig. 1.

Specific heat of pure ferro-nickels.

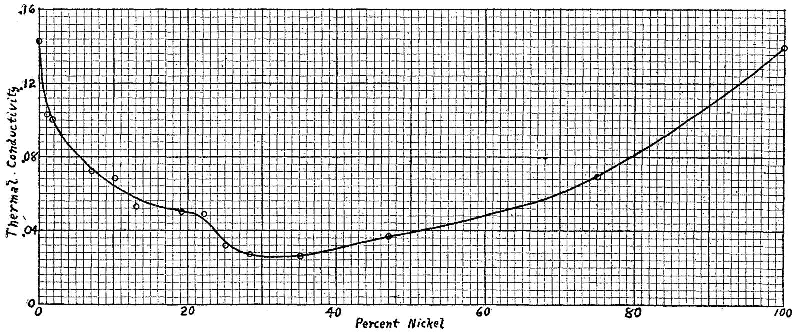

Fig. 2.

Thermal conductivity of pure ferro-nickels.

The results are in substantial agreement with those of Honda (loc. cit.) for alloys annealed in the same way, save that this investigator finds the

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[1] Abh. d. phys.-tech. Reichsanstalt, **3**, 269, 1900.

minimum conductivity at 30 per cent. nickel instead of 35 per cent. as in the present case. It may be remarked, however, that Honda's alloys were prepared from low carbon steel and ordinary commercial nickel, while those used here were composed of materials electrolytically purified.

Thermoelectric Power.—The thermoelectric powers relative to pure copper were determined with a Leeds and Northrup potentiometer. The specimens of the alloy used in this case varied in length from 3.5 cm. to 5.8 cm. and were turned down until the diameter was only .12 cm. to .18 cm. The hot junction was placed in a glass tube through which steam passed, the cold junction being kept in a stirred bath of ice and water. The average difference between the temperatures at the ends of the rod under these conditions was found to be about 96° C.

It was found that a further decrease in the diameter of the rod increased the measured thermoelectric powers somewhat but the general form of the curve was not in any way affected. The results are given in the table and in Fig. 3. It may be remarked, however, that they are perhaps not quite as trustworthy as the preceding series on specific heat and conductivity, inasmuch as the exact composition of the alloys was not as accurately known in all cases and there was some uncertainty as to how well the specimens had been annealed.

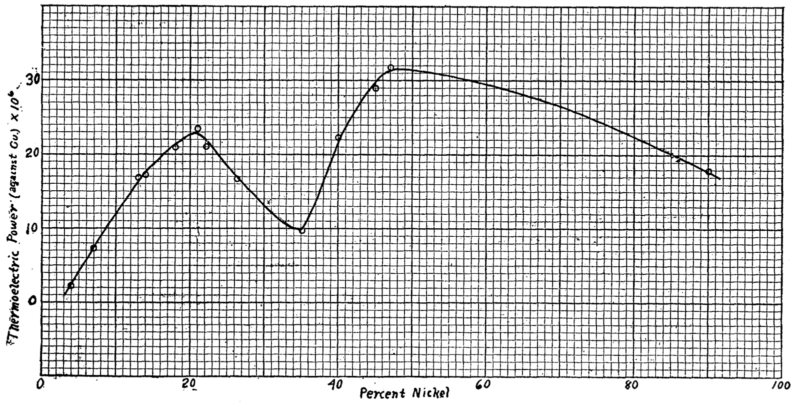

Fig. 3.

Thermoelectric power (against copper) of pure ferro-nickels.

The curve shows a marked minimum at 35 per cent. Ni. This is in agreement with the work of Haken[1] who found, particularly for the binary alloys of bismuth, marked anomalies in the thermoelectric and electrical conductivity curves for compositions giving a maximum in the melting point curve. Eagan and Emmett[2] observed a similar minimum

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[1] Ann. d. phys. 32, 291, 1910.

[2] Univ. of Wis. Thesis, 1913.

in the thermoelectric curve for bismuth-thallium alloys for a composition showing a maximum melting point.

Electrical Resistance as a Function of Temperature.—This was determined by the potentiometer method, a current of some 7.5 amperes being passed through the rod under investigation. A potentiometer of special type designed and built in this laboratory was used. The rods were heated in a nichrome wound furnace and the temperature measured with a copper-constantan thermocouple. The results are plotted in the curves of Fig. 4, while the specific resistance at 20° C. is included in the table, as well as the temperature coefficient for the range 0° to 100°. While it will be noted that the temperature coefficient for this range shows minima at 18 per cent. nickel as well as 35 per cent., it is evident from the curves of Fig. 4 that if a somewhat larger temperature range were taken the lowest point of the curve would be for the 35 per cent. alloy. The general form of these curves (aside from the minima at 26 per cent. Ni) is in agreement with the resistance curve given by Burgess and Aston (loc. cit.) for ordinary temperatures.

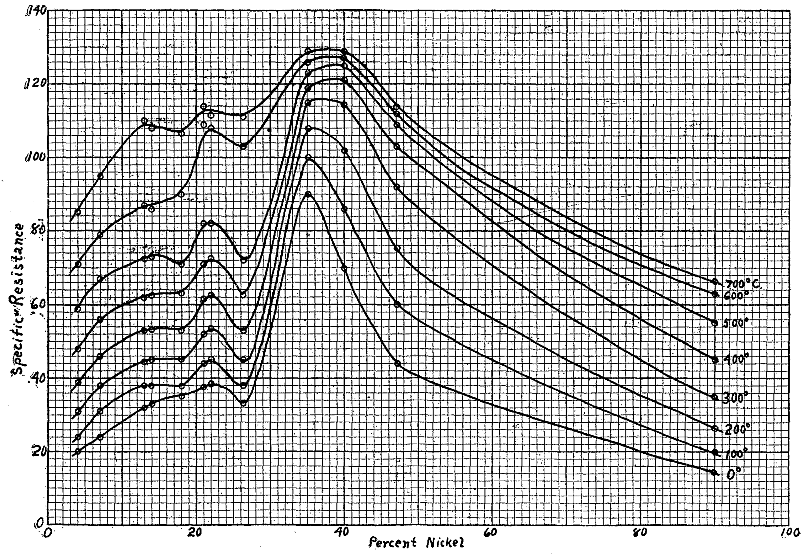

Fig. 4.

Specific resistance at different temperatures of pure ferro-nickels.

The thermal conductivity and electrical resistance measurements could be used to prove the law of Wiedemann and Franz that the thermal and electrical conductivities of a metal are proportional. A superficial examination of the table is enough to show that this is at least approximately true in this case, although a careful comparison is not possible since the two measurements were not carried out on exactly the same set of alloys. The law is very well proved for the nickel-steels, however, by Honda (loc. cit.).

Conclusions.—The results of the present work show that the 35 per cent. nickel alloy, corresponding to the composition Fe_2Ni, has physical properties more or less markedly different from the other ferro-nickels. When the measurements of these various physical characteristics are plotted as a function of the composition the following general facts are brought out: the melting point curve[1] shows a maximum, specific heat a maximum, thermal conductivity a minimum, thermoelectric power a minimum, specific resistance a maximum and temperature coefficient of resistance a minimum—all at, or very near, the composition of 35 per cent. nickel.

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[1] Vide Guertler and Tammann, Zeitschrift für Anorg. Chem., **24**, 205.