K. Honda AND S. Shimizu:—ON THE MAGNETIZATION AND THE MAGNETIC CHANGE OF LENGTH IN FERROMAGNETIC METALS AND ALLOYS AT THE TEMPERATURES RANGING FROM \(-186^\circ\) \text{C} TO \(+1200^\circ\) \text{C}.

In this Summary Vol. II. No. 3, we have published the results of our experiments on the same subject. Here the experiments were carried on by dipping the specimen in liquid air, and the results were compared with those at ordinary temperature; in the present case, the experiment was further extended to several intermediate temperatures between \(-186^\circ\) \text{C} and \(+1200^\circ\) \text{C}. Our experiment consisted of two parts: (i) the experiment at low temperatures, and (ii) that at high temperature. We tested 5 ferromagnetic metals and twelve specimens of nickel steel.* They were all examined in the form of ovoids (major axis=20 cm, minor axis=1 cm).

To obtain constant low temperatures lying between the ordinary and liquid air temperatures, a method of slow cooling was applied. The specimen-holder in our former apparatus was covered water-tightly with a brass cylinder, and a suitable amount of liquid air was poured into the interspace between the cylinder and the Dewar's tube; when the cooling reached its maximum, the observation was taken as in our former experiment. During one set of observations, which usually required several minutes, the change of temperature did not exceed one degree. The experiment was always commenced with specimens freshly annealed. The temperature of the specimen was measured by a thermoelectric couple of platinum and german silver, placed in contact with the specimen.

* These nickel steel were kindly placed at our disposal by Mr. Ch. Ed. Guillaume.
In the second part of our experiments, the magnetization at different stages of ascending as well as descending temperatures were measured, the measurement of the change of length by magnetization being left for a future occasion.

The heating was effected by means of an electric current; the heating coil was anti-inductively wounded with a platinum wire 0.4 mm thick at a rate 2 turns per cm. It was then thickly wrapped with asbestos paper. The temperature of the specimen was measured by a platinum rhodium-platinum junction placed in contact with the specimen. A current of 5 amperes passed in the heating coil was sufficient to raise the temperature of its core to 1200°C.

The magnetization was, in the usual way, measured by the magnetometric method; the magnetizing coil was prevented from its heating by a water-jacketed arrangement. It was also provided with an earth-compensating coil.

The experiment was conducted in such an order that a whole set of experiments formed a complete cycle with regard to temperature. Some remarkable results are given in the following lines.

**Change of length by magnetization.** The magnetic change of length in ferromagnetic metals is slightly affected by the cooling process: in nickel steels, its effect is tolerably large. The curves showing the effect of temperature for three nickel steels are given in Fig. 1. In every case, effect of temperature on the change of length and that on the magnetization, are parallel to each other.

In nickel steels, the magnetic change of length in weak fields gradually increases as the temperature falls, till it reaches a maximum, and then decreases. As the field becomes stronger, the maximum elongation occurs at lower temperature, and at last vanishes. These changes are common to nickel steels of higher percentages than 28.32%; for the lower percentages, the elongations for a constant field gradually increases at first and then rapidly, soon approaching to an asymptotic value, as the temperature falls.

**Magnetization.** Though the magnetizations of iron, nickel and
cobalt are slightly affected by cooling, they are, on the contrary, markedly changed by heating. The temperature at which the magnetization of these metals almost vanishes, that is, the critical temperature, are 780°C, 360°C and 1090°C respectively. These value fairly agree with these given by the previous experimentors. The weak magnetization beyond the critical point, as first observed by Curie, was also noticed. Though nickel loses nearly its magnetization as low as 360°C, yet its further reduction is very slow, and even at 1200°C, the magnetization of 12 C.G.S. is still observable. The cycle of magnetization of annealed cobalt* with regard to temperature is very singular as shown in Fig. 2. (Ann. Co.). In the ascending branch of temperature, the curve of magnetization has a small minimum at about 450°C; this point nearly coincides with the singular temperature observed by us in the change of length by magnetization. At this temperature, the sign of the length change is reversed for all fields.

The change of magnetization of reversible nickel steels by temperature is similar to that of nickel; one example is given in Fig. 2.

* The magnetization of *annealed* cobalt was first studied by Prof. H. Nagoya and Mr. S. Kusakabe.
(50.72% Ni). The manner in which the magnetization of irreversible nickel steels changes with temperature, is very striking; two examples are given in Fig. 2 (29.42%) and (24.04% Ni). As the temperature rises from −186°C, the magnetization of 29.42% Ni diminishes first slowly, then rapidly, and after passing through an inflexion point, the diminution becomes slow. The curve, passing through a second inflexion point, begins to descend very rapidly, as the critical temperature is approached. If this temperature be reached, the diminution of magnetization by heating is very little, so that the curve is nearly parallel to the axis of temperature. From the course of the curve, it seems probable that the magnetization does not altogether vanish, till its melting point is reached. As the temperature is gradually reduced, the increase of magnetization is very little; this state continues, till the temperature falls to about 100°C; then the increase becomes very rapid. Thus the magnetization of the specimen displays a remarkable hysteresis with regard to temperature.

The manner, in which the magnetization changes by temperature, is common to other irreversible nickel steels. As the percentage of nickel decreases, the concave portion of the ascending branch becomes fainter and fainter; and in 24.40% and 24.04% Ni, it almost vanishes in strong fields. The curve belonging to the last alloy is given in Fig 2 (24.04% Ni). Apparently, the forms of the two curves for nickel steels, 29.42% and 24.04% Ni are widely different from each other; but if we compare the forms of the curves of two consecutive nickel steels, we can trace transit stages from one form to another.

It deserves to notice a singular phenomenon. If at a point in an ascending branch of the temperature-cycle, the temperature be reduced to the ordinary, the path is utterly different from the ascending one. If, however, the temperature be again increased to its former value, the path nearly coincides with the preceding one; the further increase of temperature diminishes the magnetization in such a manner that the magnetization is not interrupted by the cooling process. Thus in irreversible nickel steels, the magnetization at ordinary temperature can have any value whatever within given limits, if the specimen be once heated to a suitable temperature. Becquerel, who first studied the magnetic properties of an irreversible nickel steel, found that in the alloy, there are two states of stable equilibrium; but according to our results, there are an infinite number of the states of stable equilibrium.
The critical temperatures of the alloys are given in the following table:

### Reversible Nickel Steels.

<table>
<thead>
<tr>
<th>Alloys</th>
<th>70.32%</th>
<th>50.73%</th>
<th>46%</th>
<th>36%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascending branch</td>
<td>660°C</td>
<td>490°C</td>
<td>412°C</td>
<td>255°C</td>
</tr>
<tr>
<td>Descending branch</td>
<td>—</td>
<td>460°C</td>
<td>395°C</td>
<td>240°C</td>
</tr>
</tbody>
</table>

### Irreversible Nickel Steels.

<table>
<thead>
<tr>
<th>Alloys</th>
<th>29.42%</th>
<th>29%</th>
<th>28.72%</th>
<th>28.32%</th>
<th>26.64%</th>
<th>24.41%</th>
<th>24.04%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascending branch</td>
<td>530°C</td>
<td>530°C</td>
<td>530°C</td>
<td>510°C</td>
<td>510°C</td>
<td>580°C</td>
<td>520°C</td>
</tr>
<tr>
<td>Descending branch</td>
<td>50</td>
<td>141</td>
<td>80</td>
<td>50</td>
<td>10</td>
<td>130</td>
<td>40</td>
</tr>
</tbody>
</table>

From the above tables, we notice that the critical temperature in the descending branch of the temperature-cycle generally becomes less, as the percentage of nickel decreases to 26.64%. As the content of nickel diminishes from 70.32% to 26.64%, the critical temperature falls from several hundred degrees to the ordinary temperature. It is then highly probable that 25% nickel steel, which is feebly magnetic both at ordinary and liquid air temperatures, would become strongly magnetic, if the cooling be pushed still further. It will be interesting to investigate, whether other non-magnetic alloys, which consist of a magnetic metal and a non-magnetic one, would display a similar phenomenon by cooling them to a sufficiently low temperature.

The general results as regards magnetization agree with those of J. Hopkinson, F. Osmond, Ch. Ed. Guillaume, Le Chatelier, E. Dumont and L. Dumas.

**Hysteresis-loss.** The hysteresis was studied at a temperature of room and that of liquid air. The areas of the hysteresis loops were carefully measured by a planimeter.

In Swedish iron, the hysteresis-loss decreases in weak inductions and increases in the strong by cooling it in liquid air. Fleming and
Dewar did not find any effect of cooling on the hysteresis-loss of Swedish iron. In tungsten steel, the same change occurs, with the exception of the small initial increase. In nickel, cast and annealed cobalts, the hysteresis-loss is always increased by cooling.

The hysteresis-loss in nickel steels at ordinary temperature is generally small compared with that of iron or steel. These values for reversible alloys are, however, comparable with those of nickel; but for irreversible alloys, they are all very small. Especially nickel steel of 28.32% Ni does not almost enclose any area, giving only 20 ergs for the hysteresis-loss in $B=1000$ C.G.S. If the alloys be cooled in liquid air, the hysteresis-loss considerably increases. In irreversible alloys, an enormous increase is observed.

Steinmetz’s formula giving the relation between hysteresis-loss and induction holds for nickel and annealed cobalt up to the induction of 3000 C.G.S.; it holds for cast cobalt and tungsten steel up to the induction of 8000 C.G.S.; and lastly for Swedish iron, it fails to be applicable beyond an induction of 1800 C.G.S. When, however, the specimens are cooled in liquid air, the applicable range of induction of the law is notably extended.

In nickel steels, especially in the irreversible ones, the Steinmetz’s formula does not hold, except in very weak inductions. When, however, the alloys be once cooled in liquid air, the applicable limit of induction of the low becomes greatly extended.

Concluding remarks. The fact, that two strongly magnetic metals may form a non-magnetic alloy, seems, at first sight, unfavorable to the theory of molecular magnetism. But this difficulty will disappear, if we suppose that in weakly magnetizable or nonmagnetic nickel steels, the constituent metals do not lessen or lose their property of magnetizability, but owing to some changes occurring in the molecular configuration of the alloys, the critical temperature in the descending branch of the temperature-cycle falls to a low temperature, and therefore the alloys behave as a weakly magnetic or non-magnetic alloy at the ordinary temperature. The same remark will also apply to a non-magnetic alloy which consists of a magnetic metal and non-magnetic ones. The two following facts stand in favour of the above view: (i) though the intensity of magnetization of nickel steels at ordinary temperature is not proportional to that of the constituent metals, its value at a suitably low temperature nearly follow the addition law; (ii) in irreversible alloys, the
hysteresis-loss at ordinary temperature is markedly small, which corresponds to the hysteresis of iron at high temperatures, but its value at a low temperature considerably increases, corresponding to the hysteresis of iron at ordinary temperature.

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