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Herbert Tomlinson F.R.S.

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VI. *The Effect of repeated Heating and Cooling on the Electrical Resistance of Iron.* By HERBERT TOMLINSON, F.R.S.\*

SOME of the physical properties of iron wire, even if it has been previously well annealed, can be considerably modified by repeatedly raising the metal to the temperature of  $100^{\circ}$  C., and suffering it to cool again. The internal friction, for instance, of a torsionally oscillating iron wire can be largely and permanently reduced by this process. Again, in a paper quite recently presented to the Royal Society, the author has brought forward an instance of an iron wire, which when made to go through magnetic cycles of very minute range, alternately at the temperatures of  $100^{\circ}$  C. and  $17^{\circ}$  C., was found to be permanently reduced, both in its molecular friction and its magnetic permeability, at each heating and cooling to such an extent that ultimately the former of these two physical properties became one quarter, and the latter less than one half of their respective original amounts. The large diminution of permeability and friction was also attended by a considerable lessening of the *temporary* effects of change of temperature on these properties. The object of the present investigation was to ascertain whether the electrical resistance and temperature-coefficients of iron would also be altered by the heating and cooling process. According to Matthiessen the electrical resistance of metals can be expressed by the formula

$$R_t = R_0 (1 + at + bt^2),$$

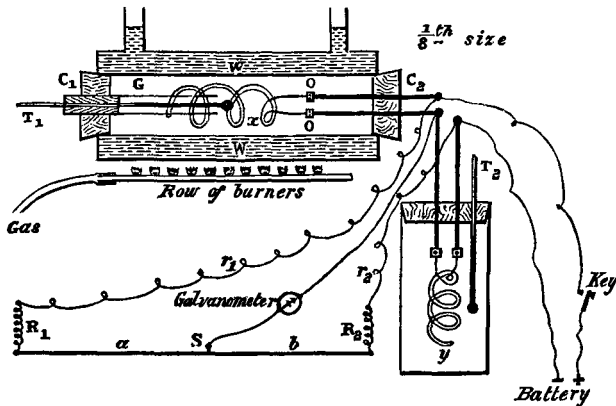
where  $R_t$  and  $R_0$  are the resistances at  $t^{\circ}$  and  $0^{\circ}$  C. respectively, and  $a$  and  $b$  are constants. For most pure metals the coefficient  $a$  is not very far from  $\cdot 00366$ , and the resistance varies, therefore, approximately as the absolute temperature; but with pure iron this coefficient is *much greater*. One of the questions which the inquiry was designed to answer was—Can the temperature-coefficient of iron be reduced by repeated heating and cooling to anything like  $\cdot 00366$ ? This question has been answered in the negative, but, at the same time, it appears that the electrical resistance itself suffers a small but decided change.

The iron wire examined formed part of a hank supplied by

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Messrs. Johnson and Nephew, and was specially prepared and annealed for the author by these makers; it was again annealed by the author himself in the following manner:—The piece of iron wire, together with several others, was placed in an iron tube about 130 centim. long; the tube and its contents were then heated, in one of Fletcher's new tube-furnaces, to  $1000^{\circ}\text{C}$ . This high temperature was preserved for several hours, and the wires were then allowed to cool slowly in the furnace. The above operations were repeated on three different days, so that eventually the wire was probably annealed as well as it could be by the ordinary method. In order to avoid any appreciable effect from the earth's magnetic force, the furnace was placed in a direction at right angles to the magnetic meridian. After the annealing the wire, which was about 120 centim. long and 1 millim. in diameter, was wrapped round with strips of paper, and wound double in a coil 5 centim. in diameter and 12 centim. in length. It was then placed in an air-chamber consisting of two co-axial copper cylinders (see fig.) connected at their extremities, and enclosing between them an annular space filled with water. The whole arrangement is sufficiently shown in the figure.



In this figure *OO* are two clamps grooved so as to receive the ends of the iron wire *x\**, the clamps themselves being soldered to stout copper connecting-rods; a German-silver wire, *y*, is similarly connected, and placed in a glass vessel.

\* If the grooves, and the ends of the wire which fit into them, be well cleaned, clamping serves quite as well, for the purpose of connexion, as soldering, and is more convenient.

$ab$  is a platinum-iridium wire of  $\frac{1}{10}$  ohm resistance;  $R_2$  is a resistance of 100 ohms, and  $R_1$  a set of resistances from  $\frac{1}{10}$  ohm to 200 ohms; the india-rubber-covered connecting-wires,  $r_1, r_2$ , have each a resistance of  $\frac{1}{20}$  ohm at the temperature of  $17^\circ \text{C.}$ ; and  $S$  is a sliding-piece which, by a suitable spring-and-catch arrangement, can be kept pressed on any part of  $ab$ . At the temperature of the room, the resistance of  $y$  is nearly equal to that of  $x$ , and  $R_1$  as well as  $R_2$  is nearly 100 ohms; consequently, any slight changes which may occur during the experimenting in the temperature of  $r_1, r_2$ , and  $ab$  do not sensibly affect the balance. The thermometers  $T_1$  and  $T_2$  register the temperatures of  $x$  and  $y$  respectively\*;  $T_1$  has its bulb in the centre of  $x$ , and is enclosed by the glass tube  $G$ ; this tube is lined with india-rubber at the extremity outside the air-chamber, so that the thermometer can, if necessary for the purpose of reading, be pulled out to any required extent without causing any cooling; the glass tube and  $T_1$  are both slightly slanted upwards to prevent the column of mercury from breaking when the temperature is falling.

For the purpose of preserving the temperature inside constant, the ends of the air-chamber are closed by corks,  $C_1, C_2$ , and the vacant spaces inside are stuffed with cotton-wool (not shown in the figure). The water in the annular space  $W$  is heated by a row of burners, made by piercing pin-holes at equal intervals in a copper tube, closed at one end, and connected at the other with the gas. By adjusting the supply of gas or by altering the distance of the row of burners from the air-chamber, any required temperature up to  $100^\circ \text{C.}$  could be maintained nearly, if not quite, constant for a considerable length of time. In 15 minutes the water could be raised to  $100^\circ \text{C.}$ ; and then, by diminishing the supply of gas so that the water only just boiled, this temperature could be kept up for 16 hours without adding more water; when it was necessary to maintain the temperature at  $100^\circ \text{C.}$  for longer periods of time, the vessel was replenished with boiling water.

It will be seen from the figure that there is a "Wheatstone's Bridge" arrangement for determining the resistance-ratio,  $x:y$ . The temperature of  $y$  varied by only a few degrees during the whole of the inquiry; and as both the actual resist-

\* Only one thermometer was used for  $T_1$  in this particular investigation, but the author generally employs, in work of this kind, three thermometers in turn. One of these thermometers is graduated from  $-5^\circ \text{C.}$  to  $30^\circ \text{C.}$ , the second from  $30^\circ \text{C.}$  to  $65^\circ \text{C.}$ , and the third from  $65^\circ \text{C.}$  to  $100^\circ \text{C.}$ ; all three thermometers are divided into tenth degrees, and have been carefully compared with the Kew standards.

ance of the coil at  $17^{\circ}$  C. and its temperature-coefficient were known, the resistance of  $y$  at any other temperature could be calculated.

It is usual in experiments with the "bridge" to close first the battery-circuit, and immediately afterwards that of the galvanometer; but the author prefers to keep the galvanometer-circuit always closed, and to observe the effect of closing the battery-circuit. It is true that in the latter case there is always a momentary throw of the needle due to self-induction in the wires, but this, with the arrangement shown above, is very slight; and with no more delay than that of two or three seconds, it can be easily ascertained whether the act of closing the battery-circuit causes *any alteration in the difference of potential at the galvanometer-terminals*\*. If, on the contrary, the former of the two methods be employed, there arises more or less inaccuracy from the presence of thermo-electrical currents set up in one or more branches of the bridge by slight variations in the temperature of the air at different parts of the room. Besides, even if the air could be maintained at perfectly uniform temperature throughout, thermo-electrical currents are always produced by the act of pressing down the sliding-piece,  $S$ , on the wire  $ab$ , and by Peltier effects.

The act of bending the wire into the form of the coil produced, as might be expected, a slight permanent change in its resistance, which was thereby increased by  $\frac{1}{4}$  per cent.; doubtless a portion, but only a small one, of the whole reduction of resistance, to be presently recorded, is to be attributed to the partial or complete removal of the effect of coiling.

When everything was ready, and the wire had been left undisturbed for several hours, its resistance and temperature were determined; the latter was then raised to  $100^{\circ}$  C., or very nearly to  $100^{\circ}$  C., and maintained thereat for at least 8 hours†; and during this period the resistance of the wire was tested several times. The wire was then permitted to cool down, and its resistance was again determined about 16 hours afterwards. The same operations were repeated again and again, until the metal showed that no sensible change of resistance was produced by the heating and cooling. The results are given in the following Table :—

\* There is always a difference of potential at the galvanometer-terminals arising from thermo-electrical effects; see what follows.

† The deviation from  $100^{\circ}$  C. never exceeded  $\frac{1}{8}^{\circ}$  C., and could in all cases be accounted for by changes in the barometric pressure.

Number of times heated to 100° C.	Specific resistance in C.G.S. units at 17° C. $R_{17}$	Differences between consecutive values of $R_{17}$	Specific resistance at 100° C. $R_{100}$	$R_{100} - R_{17}^*$	$\frac{R_{100} - R_{17}^*}{R_{17}}$	Remarks.
0	11162					
1	10942	220	16029	4962	4527	Kept at 100° C. for 8 hours; the battery-current always applied in the same direction.
2	10807	135	15796	4922	4526	
3	10772	35	15789	4985	4613	
4	10757	15	15747	4999	4633	Ditto.
5	10755	2	.....	4996	4638	Ditto.
6	10727	28	15724	.....	.....	Kept at 100° C. for 26 hours; the battery-current applied first in one direction and then in the opposite.
7	10711	16	15679	4983	4629	Kept at 100° C. for 8 hours; the battery-current applied first in one direction and then in the opposite.
8	10694	17	15674	4965	4636	Ditto.
9	10689	5	.....	.....	.....	Ditto.
10	.....	.....	15654	.....	.....	Ditto.
11	.....	.....	.....	.....	.....	Ditto.
12	10688	.....	.....	.....	.....	Ditto.

\* For the mode of calculating the numbers in these columns, see what follows.

It will be noticed that the specific resistance both at 17° C. and at 100° C. is diminished with each repetition of the heating and cooling process, until, finally, it becomes about  $4\frac{1}{2}$  per cent. less than at first. Thus, though the permanent effect on the electrical resistance is very much less than that on the permeability for very minute magnetizing forces, it is quite sensible.

At the sixth heating the wire was kept at 100° C. for 26 hours and, moreover, the battery-current was applied first in one direction and then in the opposite. These reversals of the current served to increase the rate of diminution of the resistance.

The maintaining the temperature at 100° C. for 26 hours did not diminish the resistance as much as the next two heatings and coolings taken together; evidently, therefore, the cooling exerts an influence as well as the heating. It is not, in fact, of much use prolonging each period of heating beyond 8 hours, whilst, on the contrary, a less time will hardly suffice, heating and cooling in rapid alternation being comparatively ineffectual.

Though the specific resistance of the annealed iron is permanently diminished by the heating and cooling process, this is not so with the *temporary* change of resistance arising from change of temperature; the sixth column of the Table shows that the temporary increase of resistance produced by raising the temperature from 17° C. to 100° C. is not affected by the heating and cooling process, whilst the temporary increase of resistance *per unit* becomes greater in proportion as the specific resistance itself becomes less.

The values of  $R_{100} - R_{17}$  and  $\frac{R_{100} - R_{17}}{R_{17}}$  were calculated so as to avoid, as much as possible, error arising from the *permanent* changes consequent on the heating and cooling. Let  $C_1, C_2, C_3, \&c.$ , represent the resistances of the cold wire after the first, second, third,  $\&c.$ , heatings, and  $H_1, H_2, H_3, \&c.$ , the corresponding resistances of the hot wire, then the numbers in the sixth column were obtained from  $\frac{H_1 + H_2}{2} - C_1, H_2 - \frac{C_1 + C_2}{2}, \frac{H_2 + H_3}{2} - C_3, H_3 - \frac{C_3 + C_4}{2}, \&c.$ , and those in the last column by dividing these by  $C_1, \frac{C_1 + C_2}{2}, C_3, \frac{C_3 + C_4}{2}, \&c.$ , respectively. Of course, the temperature of the room was not always 17° C., but the resistance of  $x$  at 17° C. could be calculated from its actual resistance at the temperature

at the time by means of a formula ultimately obtained for the resistance of the wire at any temperature\*. This formula was calculated from the results of a number of very careful observations at 17° C., 60° C., and 100° C., and after the heating and cooling process had ceased to affect the resistance. The formula thus obtained was :—

$$R_t = R_0 (1 + \cdot 005131 t + \cdot 00000815 t^2);$$

whilst the formula deducible from Matthiessen's results for pure iron annealed in hydrogen is

$$R_t = R_0 (1 + \cdot 005425 t + \cdot 0000083 t^2).$$

The specific resistance at 0° C. ( $R_{0.T}$ ) of the author's iron was 9808 eletromagnetic units, whilst that of Matthiessen's pure iron ( $R_{0.M}$ ) is given on the authority of the late Prof. Jenkin as 9718†. It seems not improbable that this last value is from 4 to 5 per cent. too high; for it follows from Matthiessen's researches that the resistances at any temperature of a pure metal and its alloy should be in the inverse ratio of the rates of increase of resistance at that temperature, so that

$$\frac{R_{0.M}}{R_{0.T}} \text{ should equal } \frac{\cdot 005131}{\cdot 005425},$$

which, if the author's result be assumed to be correct, would make  $R_{0.M}$  equal to 9277.

Unfortunately, Matthiessen did not determine the *absolute* resistance of iron and many of the other pure metals examined by him, and it appears from Prof. Jenkin's own statement‡ that the calculated results for these metals cannot be depended on for any great degree of accuracy. The author, therefore, ventures to express the hope that the B. A. Electrical Standards Committee may be induced to determine the absolute resistances and the temperature-coefficients of those of the pure metals which are in ordinary use.

\* Similarly for the higher temperature of 100° C.

† The number actually given by Prof. Jenkin has been multiplied by ·9889 (the value of the B.A. unit in terms of the legal ohm).

‡ See note on p. 250 of Prof. Jenkin's book on 'Electricity and Magnetism.'