

## Electrical Resistance of Alloys

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XXIX. *Electrical Resistance of Alloys.*

By R. S. WILLOWS, M.A., D.Sc.\*

THE experiments of Fleming and Dewar † and others have shown clearly the wide differences between the electrical properties of alloys and of the pure metals composing them. The well-known investigations of Matthiessen show that the resistance of alloys containing two of the metals lead, tin, cadmium, or zinc, and no other substance, can be calculated from the resistances of their constituents, when the proportions present of each metal are known. The specific resistance of all other alloys is greater than would be given by a calculation based on the assumption that the components conduct proportionally to the volume of each present. This gives rise to the curious fact that the addition of pure silver (a good conductor) to gold (a worse conductor) decreases the conductivity of the latter. Fleming and Dewar have also shown that the resistance of pure metals decreases very greatly as the absolute zero is approached, while alloys still retain a great part of their resistance.

Lord Rayleigh ‡ has advanced a theory, intended to account for these differences, which is based on the thermo-electric properties of a mixture of two metals. Liebenow §, in various publications in Germany, but at a later date, has advanced a theory which, physically, is identical with that of Rayleigh. (I might mention that in German publications the theory is always referred to as Liebenow's; Lord Rayleigh's contribution seems to have escaped notice.)

The theory is as follows:—When electricity flows from one metal to another there is an absorption or development of heat at the junction—the Peltier effect. The temperature disturbance thus created increases until the conduction of heat through the metals balances the Peltier effect at the junctions, and it sets up a back electromotive force. The

\* Read November 23, 1906.

† Phil. Mag. [5] vol. xxxvi. p. 271 (1893).

‡ Scientific Papers, vol. iv. p. 232.

§ *Encyklopädie der Elektrochemie*, Band 10.

difference of temperature at the alternate junctions is proportional to the current, so is also the back E.M.F. called into play. But a reverse E.M.F. proportional to current is indistinguishable experimentally from a resistance, so that an alloy should on these grounds possess a spurious resistance, differing in nature from that of a pure metal. Rayleigh's calculation shows that the false resistance,  $R$ , per unit length is given by

$$R = 273e^2/(\kappa/p + \kappa'/p');$$

where  $e$  = thermo-electric force of a couple for  $1^\circ$  difference of temperature between the junctions;  $\kappa$  and  $\kappa'$  are the heat conductivities of the metals in ergs;  $p$  and  $p'$  are the proportions by volume in which the two metals are taken. The temperature is supposed to be near  $0^\circ$  C.

It will be noticed that  $n$ , the number of couples per unit length, does not enter into the above expression. The number co-operating is indeed increased by finer subdivision, but the efficiency of each is decreased owing to the readier conduction of heat between the junctions. An alloy of equal volumes of copper and iron should have a false resistance amounting to 1.5 per cent. of that of copper, as is readily shown by substitution of the appropriate numbers in the above formula.

It may be noted in passing that this expression shows that it is possible always to choose the proportions of the metals present so that the resulting alloy shall have a maximum resistance. For  $p + p' = 1$ ,

$$\therefore R = \frac{273e^2}{\frac{\kappa}{p} + \frac{\kappa'}{1-p}},$$

and for a maximum or minimum  $dR/dp = 0$ ;

$$\text{whence } \kappa/p^2 - \kappa'/(1-p)^2 = 0;$$

or

$$p = \frac{1}{1 + \sqrt{\frac{\kappa'}{\kappa}}}.$$

The positive sign is to be taken with the square root, since

the other sign would make  $p$  come outside the limits 0-1, and this value it is readily seen corresponds to a maximum  $R$ .

It appeared possible to put this false resistance in evidence in two ways, one direct, the other not so. It was only after working for a considerable time that I became acquainted with Liebenow's work, which is entirely concerned with the indirect method.

This paper is a description of the attempts I have made to separate the true and false resistances directly. Suppose a current runs through an alloy and that it sets up a back E.M.F.: if it is now quickly reversed, this inverse E.M.F. will at first assist its passage, and more will flow in the second direction than in the first, or, what comes to the same thing, the resistance will appear to be less for the quickly reversed current than for the steady direct one. As the temperature of the junctions will be equalized rapidly on account of their small distance apart, the current reversals must be rapid. I therefore used an alternating current.

The alloy to be tested formed one of the arms of a Wheatstone's bridge, the adjacent arm being a simple metal such as copper or lead, generally the latter on account of its greater resistivity. The resistances were first balanced for alternating and then for direct current. The pure metal possesses no spurious resistance, and hence the apparent resistance of the alloy should decrease when the alternating current is used.

The figure (p. 430) shows the arrangement of apparatus.

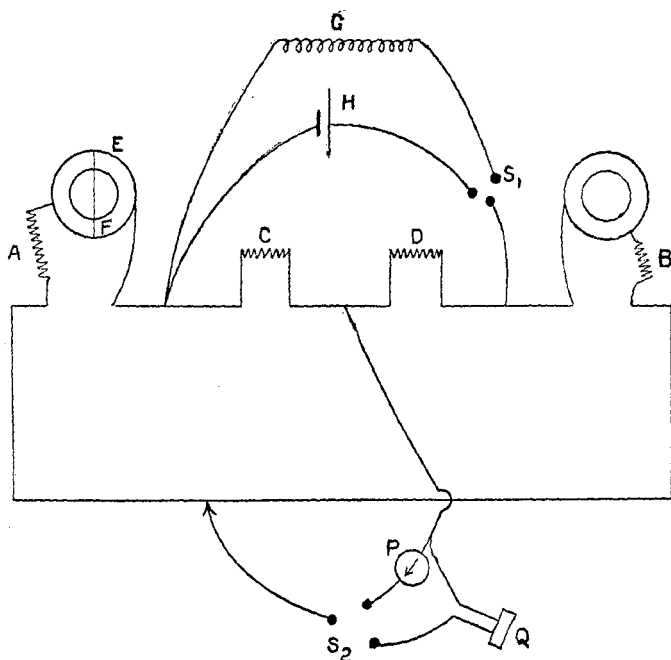
A is the resistance-coil of alloy; B the copper or lead resistance made from specially purified material obtained from Johnson and Matthey; C, D, are two coils of manganin or eureka wire wound on the same bobbin; G is the secondary of a small induction-coil; H, a Leclanché cell; P, a galvanometer; Q, a telephone specially wound for bridge work, or a vibration galvanometer;  $S_1$ ,  $S_2$ , mercury-paraffin switches by means of which the source of current or the detector could be changed.

There is, in addition to the false resistance of the alloy, the skin effect, arising from the concentration of current in the outer layers, to be taken into account. If  $R$  is the true resistance of a wire of length  $l$  to steady currents, then the

resistance to currents of moderate frequency and of simple periodic form is

$$R' = R \left( 1 + \frac{1}{12} \frac{\mu^2 p^2 l^2}{R^2} \right),$$

where  $\mu$  is the permeability and  $p = 2\pi$  (frequency). The wave-form of the current used was not known, but the second term in the bracket was made small by using wires of small diameter. Were any skin effect present, only the difference between that in lead and in the alloy would be given by the experiment.



For the same frequency the value of this term depends on  $l/R$ , and this is greatest for the pure metal, and hence if  $\mu = 1$ , the skin effect, when it first becomes appreciable, would make the alloy appear to decrease in resistance when referred to copper or lead as standard.

All the coils in the bridge were made of wire 0.33 mm. in diameter, formed after the manner given by Chaperon, by first winding a definite number of turns in the right-handed

direction and then an equal number the opposite way. The resistance of each was 3 ohms approximately; the induction in the arms by this method was rendered very small, but was still large enough, with these low resistances, to give a flat minimum in the telephone. With an ordinary set of coils out of a resistance-box it was impossible to obtain a balance. In order to render the minimum sharper the method of Rayleigh was adopted\*. E is a wooden ring of 4 inches diameter, F one of 2 inches; the smaller can be rotated round a common diameter of the two. Each ring carries three turns of copper wire, 0.33 mm. diameter, joined in series, and the whole arrangement is in series with A. By rotating the coil F, the induction in the arm could be varied within narrow limits. A similar pair of coils is in series with B. By this means the balance point on the wire of the bridge with alternating current could be found readily to 1 mm., generally much nearer, and as the resistance of 1 mm. of the bridge wire was 0.0006 ohm, this corresponds to a minimum accuracy of about 0.02 per cent.

Various current interrupters were used. In the preliminary experiments a secohmmeter and the galvanometer were tried, but soon abandoned, because thermo-currents were troublesome, and also because I desired to get a greater range of frequency. Finally a vibrating wire with mercury contact was used in the low-frequency experiments. This broke the primary circuit of a small induction-coil, the secondary of which was joined to the bridge, and it possessed the advantage that it could readily be tuned to unison with the vibration-galvanometer used as detector. For most of the other observations a wheel interrupter was used. This was made by letting into the circumference of a disk of beech-wood, 1 foot in diameter, about 120 pieces of brass whose width along the circumference was about  $\frac{1}{10}$  inch, the whole being carefully turned. Pressing on the circumference were two springs which completed the circuit through the brass pieces as the wheel revolved when driven by a motor. A small condenser was connected to the springs to prevent sparking.

The bridge was balanced first with alternating current by shifting the movable contact and adjusting the coils E, F

\* Phil. Mag. Dec. 1886.

until the inductances as well as the resistances of the arms were equal; then with direct current. The coils A and B were then generally interchanged and the observations repeated. Mr. F. G. Bratt helped me considerably by taking readings alternately with me.

The alloys used were eureka, brass, platinoid, German silver, platinum-iridium, and platinum-silver. The frequency of the current varied between 10 and 980 per second.

No certain differences could be detected between the resistance of an alloy to direct and alternating current at temperatures  $20^{\circ}$  and  $100^{\circ}$  C.

As already mentioned, Fleming and Dewar found the resistance of a pure metal very small at low temperatures, while that of alloys was not greatly changed. It seemed possible, therefore, as the temperature was reduced, that the true resistance of an alloy might decrease and the false resistance become relatively great. Experiments similar to those described above were therefore made with alloys at the temperature of solid  $\text{CO}_2$  and of liquid air, but in no case could any false resistance be found.

Other experiments with a 20-ohm coil of German silver balanced against one of lead gave similarly negative results. Whether this is due to the frequency being too small to overtake the equalisation of temperature of the junctions, future experiments, which I hope to carry out, will perhaps determine.

The experiments of Hagen and Rubens\* on the reflecting and emissive powers of metals for infra-red rays do not help us. They show that the electrical conductivity can be found by measuring the reflecting or emissive powers to within a few per cent. Alloys do not occupy an exceptional position. The experiments do not put in evidence the magnet properties of iron and nickel.

In any case indirect evidence in favour of Rayleigh's theory is not wanting. Liebenow gives the results of his calculation in a form involving two constants, which he calls the inner molecular heat conductivity of the metals. By assigning proper values to these the formula expresses well, in some cases such as gold and silver excellently, the relation

\* *Annal. d. Physik*, vol. ii. p. 873 (1903).

between resistance and composition when applied to the measurements of Matthiessen, Feussner, Haas, and others. They are not, however, altogether convincing. The heat conductivities to be ascribed to the different molecules seem to bear no relation to the conductivities as usually measured in the mass. Thus, taking the heat-conduction of copper as unity, silver requires to be taken as 2.3 and gold as 2, while copper-zinc has the value 3 ascribed to it.

I might also point out that a frequent constituent of the high resistance alloys in common use is nickel, a metal for which the Peltier effect and other thermo-electric properties are strongly pronounced.

In conclusion I have to thank the Government Grant Committee of the Royal Society for help in defraying the cost of this research.

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#### DISCUSSION.

Prof. J. A. FLEMING expressed his interest in the paper and said Lord Rayleigh's theory was ingenious, but it seemed to him that it presupposed a coarseness of structure in the alloy. An alloy was probably a substance of the nature of a solution with a fine structure, and it was difficult to see how thermoelectric E.M.F.s could be brought into play without discontinuity of material. Considering an electric current as a passage of electrons, Prof. Fleming pointed out that some of the electrons would pass through the spaces between the molecules in the material and others would impinge against the molecules themselves or the molecular aggregates. The latter would set up perturbations which would produce heat and corresponding electric resistance. If an alloy were supposed to consist of molecular aggregates while a pure metal consisted of molecules, more electrons would pass through material in the latter case than in the former. This would produce a greater quantity of heat, and correspond to a higher resistance in the case of the alloy.

Mr. A. CAMPBELL said that shortly after Lord Rayleigh advanced his theory he made some experiments to try to detect if alloys showed changes of resistance when tested



with alternating and direct currents. The alloy selected was ferro-nickel, as it was expected that this would show the effect strongly, as the constituents give a strong thermo-electric E.M.F. A current was sent through a long ferro-nickel wire doubled back on itself, and this current was measured by a Kelvin balance, while the voltage on the ends of the wire was measured by a Kelvin electrostatic voltmeter (reading to 1 in 1000). No difference could be detected between the apparent resistance with direct current and with alternating current of frequencies up to 80 per second (the usual correction for contact difference being found and applied).

Mr. W. DUDDELL suggested that the Author should proceed with his experiments using very much higher frequencies.

### XXX. *Auroral and Sun-spot Frequencies Contrasted.*

*By C. CHREE, Sc.D., LL.D., F.R.S.\**

§ 1. DURING several recent investigations I have had occasion to contrast the annual variation in years of many and in years of few sun-spots of elements such as the diurnal range of the magnetic declination, or the frequency of occurrence of magnetic storms. The formula first advanced by Wolf

$$R = a + bS \quad . \quad . \quad . \quad . \quad . \quad (1)$$

as connecting  $R$ , the range in the mean diurnal inequality of declination throughout the year, with  $S$  the corresponding sun-spot frequency— $a$  and  $b$  being constants—can be applied with considerable accuracy to the range in individual months of the year, and to magnetic inclination, horizontal force and vertical force, as well as declination. But taking any one element,  $a$  and  $b$  are different for the different months of the year, and  $b/a$  is in general decidedly larger for winter than for summer.

Suppose, now, that dashed letters refer to a winter, undashed to a summer month, and that suffixes 1 and 2 relate

\* Read November 23, 1906.