pounds of metal very hot—quite hot in proportion as it is thick. Now when that engine is shut down heat is there as insensible heat of the metal, and the jackets are full of water—X pounds of water and Y pounds of hot metal. If the weights and heats involved are figured out you will find in a big engine there is enough heat in the metal to evaporate all the water to steam and you would still have some left to conduct out to more distant parts, which should be cold—parts which are designed to be cold, but which, when hot, crack. Especially is that true when after such a shut-down and a general heating somebody starts the engine and shuts a lot of cold water up against the surface. That condition can be eliminated only by completely independent jacket-water circulators separately driven by another engine, which permits the running of the water so long as water comes out from the discharge with any rise in temperature over the intake. In other words, the water should be continued through such an engine until it ceases to become warm, and that may be from twenty minutes to half an hour after the shutdown, depending on the size and style of machine.

A similar discussion could be carried on about other auxiliaries. This question of auxiliary arrangement and starting by an auxiliary engine is just as important for study as the engine itself. There is just as much room for improvement as in the engine structure, as a structure, or the engine parts that are concerned with its functional operation.

Getting back now to the beginning, it must be admitted, and the more you study it the more willing you will be to admit it, that, while we have made very considerable progress with the heavy-oil engine, that progress is by no means ended. In fact, we can go much further yet than we have already gone, and we can make the heavy-oil engine meet conditions it has heretofore failed to meet.

THE INFLUENCE OF HEAT TREATMENT ON THE ELECTRICAL PROPERTIES OF STEEL.

THE INFLUENCE OF HEAT TREATMENT ON THE ELECTRICAL AND THERMAL RESISTIVITY AND THERMO-ELECTRIC POTENTIAL OF SOME STEELS.*

By Edward D. Campbell and William C. Dowd.

(University of Michigan, Ann Arbor, U. S. A.)

The principal object of the present investigation—which is far from being complete—was to conduct a preliminary study of the correlation of electric and thermal properties of steels in the light of the solution theory if accepted in the full sense of the term.

Although an apparent connection between thermal and electrical conductance in metals had previously been noted by Forbes, it was the systematic work of Wiedeman and Franz in 1854 which demonstrated the relationship was probably a definite one. If this were the case it would be reasonable to expect both electrical and thermal restivity in metals might be due to the same atomic or molecular mechanism. Although numerous investigators studied the relation existing between electrical and thermal resistivity in metals subsequent to Wiedeman and Franz's publication, it was the ex-

---

haustive work of Jaeger and Disselhorst which demonstrated that the ratio of the electrical to the thermal resistivity is approximately constant for pure metals, but does not hold equally well for impure metals or alloys. In 1897 Schulze[†] measured the thermal and electrical conductivities of five carbon steels and one manganese steel, and showed that the Wiedeman and Franz law did not hold in the case of these metals. It is now generally conceded that the Wiedeman and Franz law—that is, the ratio of the electrical to the thermal resistivity in absolute units—holds quite closely for pure metals, being about 6.5×10^{-14}. It does not, however, hold very closely for impure metals or alloys, although in general any marked change in electrical resistivity is accompanied by a corresponding change in thermal resistivity. During the past twenty years physicists have carried out a great number of experiments in order to determine with an increasing degree of accuracy the correlation of electrical and thermal resistivity in metals, with special view to the influence of the temperature at which the measurements were made on this relationship. In almost all this work metals or alloys of metals other than iron were employed. Very few, if any, systematic measurements of the thermal resistivity of steel have been made, although the fact that there is a close relationship between the chemical constitution and electrical resistivity of steel has been recognized for more than fifty years, and has served as a basis for many researches.

Although the solution theory of metals, as it is now termed, was first advanced more than a century ago, to the great majority of physicists and metallurgists the term is almost a meaningless phrase, since they still refuse really to accept as a mental concept the essential unity of the mechanism of metallic and aqueous solutions. They all recognize and take into account the part played by the solvent as differentiated from that played by the solute in ordinary solutions, and yet, when studying the properties of metallic solutions, many of them refuse to recognize the essential unity of mechanism, and make little or no effort to differentiate between the part played by the solvent and that by the solute. It would seem entirely possible that, if metallic solutions were regarded from exactly the same viewpoint as ordinary solutions, reasonable explanations for many well-known phenomena might be found which cannot be satisfactorily explained in any other way.

In 1915 one of the authors[‡] gave experimental evidence to substantiate the conception that total electrical resistivity of steel must be considered as made up of two components—first, that due to the solvent, and, second, that portion due to the carbides in solution; the effect of these latter on the electrical resistivity being proportional to the concentration of the carbides actually in solution. It was there suggested that, as in aqueous solutions, it is the molecules in solution which are capable of reacting with different forms of energy, and consequently the electrical resistivity would be dependent on the molecular concentration of the carbides in solution, since by their reactivity these carbides would cause electrical energy to disappear as such and reappear in the form of heat.

In a later paper[*] the dependence of the electrical resistivity on the concentration of the carbides in solution was confirmed, and it was further shown that if carbides are the only solutes present in noticeable amounts the thermo-electric potential due to dissolved carbides is a function of the concentration. In these same papers it was further shown that electrical

†"Annal. Phys. Chem.," vol. lxiii, p. 28, 1897.

‡"Journal of the Iron and Steel Institute," 1915, No. II, p. 164.

*"Journal of the Iron and Steel Institute," 1916, No. II, p. 268.

conductance is almost entirely through the solvent, while electrical resistivity is only in part due to the solvent, frequently as much as 80 per cent or more of the total resistivity being due to the solutes in solution.

Experimental.—The experimental bars used were all machined down to a uniform size of 6 mm. square by 15 cm. in length from stock samples of larger bars furnished by the courtesy of the same companies which have supplied us with bars in our previous work. The composition of the steels used in the present research is given in Table I.

In annealing the steels used a number of sample bars were usually packed in an electrically-heated furnace in such a way as to avoid oxidization, and the temperature raised overnight to that stated as the temperature from which each sample was annealed, after which the furnace was allowed to cool for 24 hours and the large sample bars removed. It was from the sample bars thus annealed that the small experimental bars used for quenching were machined. All temperatures, whether of annealing or quenching, were measured by means of standard platinum-rhodium thermocouples standardized at intervals against the melting-point of pure silver taken at 961 degrees C.

The method of hardening the small bars was essentially the same as that employed in this laboratory for some years and described in detail in 1915.†

The bars to be quenched were suspended in an electrically-heated furnace so designed that, no matter how long they were kept in the furnace, there was no oxidization, and carburization, if occurring at all, did not exceed 0.02 per cent. The bars were kept in the heated chamber as a rule one hour, the temperature being measured by a thermo-couple placed 2 mm. or 3 mm. from the bars under treatment. The quenching bath was a large volume of ice-water, and, as in our previous work, the time required to transfer a bar from the furnace to the quenching bath was a little less than one second, the same amount of time being required to cool the bar from the quenching temperature to below a red heat. Experience in this laboratory has tended to show that bars which are perfectly clean and bright cool somewhat more quickly on quenching than the same-sized bars which have been heated in a fused salt bath. These latter, on withdrawing from the heating bath, are covered with a thin film of fused salt, which appreciably retards the cooling effect of the water. Enough bars of each kind of steel were quenched to enable the specific resistivity and thermo-electric potential to be measured at the same time. Thermal resistivity was measured on one of these bars after the other measurements had been made. After all the bars had been quenched they were carefully polished and the measurements of specific resistivity, thermo-electromotive force. and thermal resistivity made with no more delay than was necessary. Numerous experiments in this laboratory have shown that, on account of the instability of the solid solution produced by quenching steel in cold water, the specific resistivity and correlated properties will fall off very appreciably even at room temperature within a comparatively short time.

The specific resistances were measured in all cases on bars kept immersed in an oil bath and maintained at a constant temperature of 25 deg. C. The method of determining specific resistance was the same as that heretofore employed, that is, by measuring the fall in potential between knife-edges clamped to the bar 10 cm. apart, while a current of constant density was flowing through the bar.

On account of the rapid change in chemical constitution of hardened steel with increase of temperature it was thought best to make the measurements of specific resistances, thermo-electromotive potential, and ther-

† "Journal of the Iron and Steel Institute," 1915, No. II, p. 164.

TABLE I.—*Composition of Steels.*

Steel.	Carbon.	Manganese.	Phosphorus.	Sulphur.	Silicon.	Copper.	Nickel.	Chromium.
	per cent.	per cent.	per cent.	per cent.	per cent.	per cent.	per cent.	per cent.
INI	0.018	0.016	0.005	0.018	—	0.018	—	—
H57	0.57	0.11	0.010	0.020	0.17	—	—	—
INC	1.184	0.016	0.005	0.018	—	0.018	—	—
C5	0.045	0.189	0.013	0.016	0.155	—	—	—
H1	0.18	0.67	0.007	0.019	0.18	—	3.45	—
M8	0.326	0.405	0.013	0.026	0.162	—	4.48	—
H6	0.14	0.44	0.009	0.008	0.11	—	4.12	t.61
8N1	1.110	0.40	0.020	0.038	1.20	0.06	0.31	0.348
8N3	0.104	0.122	0.03	0.025	3.649	—	—	—
MN1	1.150	11.57	0.055	0.023	0.25	—	—	—

TABLE II.—*Table showing Specific Resistance, Relative Thermal Resistivity, and Thermo-Electromotive Potential of Annealed Steels.*

Steel.	Temperature of Annealing.	Specific Resistance in Microhms.	Relative Thermal Resistivity.	Thermo-Electromotive Potential against Ingot Iron in Microvolts.
	deg. C.			
INI (1)	778	10.64	1.0	—
H57 (2)	903	15.28	1.25	116
INC (3)	960	15.90	1.35	90
C5 (4)	903	18.05	1.47	128
H1 (5)	700	25.16	1.99	310
M8 (6)	—	25.36	2.03	371
H6 (7)	718	32.24	2.38	232
8N1 (8)	950	41.58	2.84	362
8N3 (9)	985	53.87	3.17	556
MN1 (10)	810	54.25	3.78	334

TABLE III.—*Table showing Specific Resistance, Relative Thermal Resistivity, and Thermo-Electromotive Potential of Hardened Steels.*

Steel.	Temperature of Quenching.	Specific Resistance in Microhms.	Relative Thermal Resistivity.	Thermo-Electromotive Potential against Ingot Iron in Microvolts.
	deg. C.			
INI (1)	Annealed	10.64	1.0	—
H57 (2)	902	22.08	1.85	186
H1 (5)	902	27.74	2.22	318
M8 (6)	830	29.72	2.27	368
	900	—	—	—
H6 (7)	830	34.77	2.68	216
C5 (4)	830	37.41	2.99	320
	902	—	—	—
INC (3)	830	41.64	3.27	353
	902	—	—	—
8N3 (9)	902	54.72	3.57	556
8N1 (8)	830	56.38	3.93	324
MN1 (10)	902	69.80	5.35	554

mal resistivity without allowing the temperature of the bars at any time to exceed 35 deg. C. or 40 deg. C. The thermo-electromotive force measured, therefore, was that due to the temperature gradient between 0 deg. C. and 25 deg. C. The method employed was a modification of the one used a year ago and described in detail in one of our previous papers.* In the method used in the present work three bars of the same steel and subjected to the same heat treatment were clamped together to form a triple compound bar, to the ends of which were attached, by means of pure iron clamps, the annealed ingot iron leads connecting the ends of the compound bar with the galvanometer by means of which the potential was measured. One end of the compound bar was maintained, as in our previous work, at 0 deg. C. by means of crushed ice, while the other was immersed in the same oil bath as that used for specific resistivities, which was maintained at 25 deg. C. Thus the thermo-electromotive force, measured and expressed in micro-volts, represents the difference in thermo-electromotive potential of the steel in question and pure iron over the temperature gradient from 0 deg. C. to 25 deg. C.

As the work herein described is in a sense a preliminary study of the correlation of electrical and thermal resistivities without any attempt to determine the absolute relationship, the thermal resistivities so far determined have all been relative, that of pure ingot iron being taken as unity. It is hoped that later new determinations of thermal resistivities will be made with improvements in the apparatus which will enable such measurements to be made under more favorable conditions, and with a higher degree of precision, so that the results may be reduced to absolute units. The method employed of measuring the relative thermal resistivities herein given was one of the stationary temperature type, the technique of which was developed under the direction of Dr. Carleton V. Kent, of the Department of Physics. The detailed description of this method of Dr. Kent is given in the "Physical Review" of 1917.

The method of determining the relative thermal resistivities is briefly as follows: The bars, 6 mm. square and 15 cm. in length, are provided with two holes a little less than 1 mm. in diameter and 4½ mm. in depth, one hole being 5 mm. from the cold end of the bar and the other 10 cm. from the same end. These holes are for the insertion of fine copper-constantan thermo couples, by means of which the difference in temperature between each of the holes and the surrounding space is measured. The holes were filled with paraffin oil before inserting the thermocouples, a better thermal contact being thus obtained between the couple and the steel than when the oil was not used. About 3 cm. of one end of the bar was inserted in a small heating coil, by means of which the temperature of the bar at the hot end could be easily raised and maintained constant for any desired length of time. The bar, supported in the heating coil and with thermocouples in position, was inserted into the center of a heavy steel cylinder, 20 cm. inside diameter and 40 cm. long, and closed at the inner end with a heavy steel plate. This steel cylinder was, in turn, boxed in, in order to avoid local air currents. The mass of the metal—something more than 20 kg.—was sufficient to maintain reasonable constancy of temperature throughout the interior during a given experiment. After a bar whose thermal resistivity was to be measured had been inserted into the steel cylinder, a current was turned on through the heating coil until the thermocouple showed a rise of about 10 deg. C. The copper-constantan thermocouples used were made of very fine wires, each being calibrated against a standard thermometer. The couples gave a deflection of about 6

* "Journal of the Iron and Steel Institute," 1916, No. II, p. 268.

mm. per each degree, so that temperatures could be readily measured to within less than 0.05 deg. C. Since all the bars were of the same dimensions, the thermocouple holes were the same distances from the cold end in every case, and the temperature of the higher point of measurement was substantially constant in all cases, the difference in temperature at the cold and hot points of measurement must have been directly dependent upon the thermal resistivities of the bars. Usually from 1½ to 2 hours were required for the system to come to equilibrium. When this had been attained, the ratio of the temperature difference at the hot and cold ends of the bar was calculated. Dr. Kent has shown that the ratio

$$\frac{\theta_1}{\theta_2} = \cos \alpha \ 1,$$ in which simplified equation $\alpha = \sqrt{\frac{hp}{cq}}$

where h is the heat lost to the enclosure from 1 sq. cm. of the surface per degree excess temperature, p is the perimeter, c is the conductivity, and q is the cross-section of the bar. From mathematical tables giving hyperbolic functions, α 1 may be found from the experimentally determined temperature ratio $\frac{\theta_1}{\theta_2}$. Since we are interested in the reciprocals of the conductivity or the resistivity, the relative resistivities may be easily found from the $(\alpha \ 1)$'s, as h, p, q and 1, the distance between the hot and cold points of measurement, are the same for each bar. The resistivities would, therefore, be directly proportional to the square of the $(\alpha \ 1)$'s.

Fig. 1. CURVES SHOWING RELATIVE THERMAL RESISTIVITY & THERMO E.M.P OF ANNEALED STEELS PLOTTED AGAINST SPECIFIC RESISTANCE.

Fig. 2. CURVES SHOWING RELATIVE THERMAL RESISTIVITY & THERMO E.M.P OF HARDENED STEELS PLOTTED AGAINST SPECIFIC RESISTANCE.
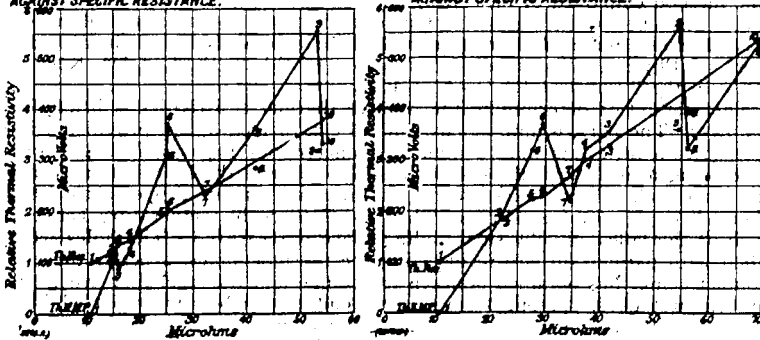
The results of the measurements of the specific resistance at 25 deg. C., of the relative thermal resistivity, and of the thermo-electromotive force of the nine steels in the annealed condition, are given in Table II, in which the steels are arranged in order of increasing specific resistance. In this table is also given the specific resistance of the pure ingot iron which is taken as unity in the determination of relative thermal resistivities and which is also used in opposition to the different steels when determining the thermo-electromotive potential. The small numbers in parentheses following the names of the steels as given in Tables II serve to identify the points corresponding with each steel, as shown graphically in Figs. 1 and 2.

In Table III are given the corresponding measurements made on the same steels as those given in Table II, but with the steels in the quenched or hardened condition. The steels are again arranged in order of increasing specific resistance, but it will be noted, from the small figures in

parentheses following the name of each steel, that the order of arrangement of the steels in the hardened condition is quite different from what it was when the steels were annealed.

In order to bring out the correlation of the thermal and electrical resistivities as influenced by chemical constitution and heat treatment, the results of the measurements given in Tables II and III are shown graphically in Figs. 1 and 2. In these the specific resistances in microhms are shown on the abscissæ, while the corresponding relative thermal resistivity and thermo-electromotive potentials are shown on the ordinates. It will be noted that the curve of relative thermal resistivity is approximately a straight line except for two points, 8 and 9, of the steels SN1 and SN3, both of which are high silicon steels, the silicides apparently giving a distinctly higher ratio of electrical to thermal resistivity than do carbides or other solutes.

A study of the data given in Tables II and III, and of the curves shown in Figs. 1 and 2, reveals some interesting relationships, especially if viewed in the light of the solution theory of steel accepted in the full sense of the word. If steel is regarded as made up of a solvent and solutes, we may get an approximate idea of the relationship of that portion of the electrical resistivity due to solutes to that portion of the thermal resistivity due to solutes by subtracting from the total specific resistance the specific resistance of pure iron (10.64), and from the total relative thermal resistivity that of pure iron (1.00), and then finding the ratio of the electrical resistivity to the relative thermal resistivity. The ratio of the electrical resistivity to its relative thermal resistivity of pure iron would, of course, be 10.6. If, in the case of the annealed steels, we calculate by the method above just suggested—the ratio of the electrical resistivity to the relative thermal resistivity—we find this varies from 14.3 to 19.7 in the case of SN3, in which the solute is almost entirely silicide. In the case of the hardened steels the ratio of the electrical resistance to the relative thermal resistance due to solutes varies from 13.4 to 17.4, the highest ratio again being due to that of SN3, containing the highest concentration of silicides. These ratios are all noticeably higher than the ratio found in the case of pure iron solvent and confirm what has been known for many years—that the Wiedeman and Franz law does not hold in the case of impure metals or alloys, the electrical resistivity of such metals increasing more rapidly than the thermal resistivity. In all the steels under examination the effect of quenching has been to increase both the electrical and thermal resistivity, the extent of this change being closely connected with the percentage of carbon in the steels. This would be expected, since it is the carbides which precipitate from solution when the steel is annealed and again pass into solid solution when heated above Ac3 just before quenching

In 1916* a hypothesis to account for electrical resistivity in steels was advanced. This hypothesis assumed the essential unity of mechanism of solid solutions and of aqueous solutions, and attributed that portion of the total specific resistivity due to carbides in solution to the transformation of electrical energy into heat, this transformation being due to the fact that it is those molecules in solution that are most reactive toward any form of energy. If heat is assumed to be made up of two forms of motion, one portion being electronic and the rest atomic or molecular motion, we might easily find a reasonable explanation for the correlation between electrical and thermal resistivities based on the solution theory in the full sense of the word. If molecules of solutes in solution are capable of reacting with electrical energy and transforming a portion of this

* "Journal of the Iron and Steel Institute," 1916, No. II, p. 268.

electronic motion into atomic or molecular motion, thus producing electrical resistivity, it would be only reasonable to expect that the same molecules in solution which could transform electronic motion of electricity would also be capable of transforming that portion of heat which exists as electronic motion into atomic or molecular motion. Under this conception we would expect a close relationship between the electrical and thermal resistivities of steel, since they both become dependent upon the chemical constitution.

When carbides are the only solutes present to any considerable extent it was shown in the paper before referred to that there is a parallelism between the thermo-electromotive potential of these carbides and the specific resistance, both being dependent on the concentration of the carbides in solution. From the curve of the thermo-electromotive potential shown in Figs. 1 and 2 it will be evident that the thermo-electromotive potential is dependent upon the chemical composition of the solutes as well as on the concentration. Under the conception of the essential unity of mechanism of metallic and aqueous solutions the assumption that the thermo-electromotive potential of solutes in solid solution is exactly analogous to the solution tension of electrolytes in aqueous solution would offer a simple explanation for the changes in thermo-electromotive potential due to differences in chemical composition and heat treatment. If a cell be set up with an aqueous solution of a single electrolyte A, the electro-motive force of such a cell will be dependent on the chemical composition and concentration of the electrolyte. If a second cell be set up with an electrolyte B, of higher solution tension than A, the electromotive force of the second cell will be higher than that of the first for a given concentration. If a cell be set up with a mixture of these electrolytes, A and B, the electromotive force of such cell will not be additive, but will be intermediate between that of A and B, never reaching as high as when B alone is present. An exactly analogous change will be found in the thermo-electromotive potential of steels when the concentration of the solutes in solution is changed by heat treatment. When the thermo-electromotive potential of the solute in solution, other than carbides, is higher than that due to carbides in solution, the thermo-electromotive potential of such steels in the hardened condition tends to be lower than that of the same steel annealed, since in the annealed condition the carbides are very largely precipitated. This is most strikingly illustrated in case of SN1, where we find a distinct drop in thermo-electromotive potential brought about by quenching, although the specific and thermal resistivities are both markedly increased due to the increased concentration of the solutes in solution.—" Engineering."

EMERGENCY FLEET ENGINES.

The 700-H.P. engine building at the Buckeye Engine Company, Salem, Mass., is illustrated on the opposite page. The cylinder diameters in inches are 15½, 26, and 44. Stroke is 26 inches. Piston valves are used on all cylinders, their diameters in inches being 7 1/16, 14 1/16, and 15. Length of valves is 3 feet 15/16 inch.

The engine frame consists of forged front columns, 4½ inches in diameter, and cast A-shaped rear columns which carry the crosshead guides. The columns are about 7 feet high. Shafts are 8⅝ inches in diameter, with cranks set at 120 degree angle.

The details of design follow conventional designs.—ED.