

THE PHYSICAL REVIEW.

THE EFFECT OF LOW TEMPERATURE ON SOME OF THE PHYSICAL PROPERTIES OF A SERIES OF IRON-CARBON ALLOYS.

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THE series of experiments described below was undertaken with the view of determining how the temperature of liquid air affects the magnetic permeability, the magnetic hysteresis and the expansion coefficient of a series of iron-carbon alloys; and how these properties change with varying chemical composition.

The effect of low temperatures on the magnetic hysteresis, magnetic permeability and electrical conductivity has been studied to some extent before but with alloys of iron of which the chemical composition and definite, previous heat treatment were in many cases unknown.

A very exhaustive study of the effect produced by liquid air temperatures on the mechanical properties of iron and its alloys has been made by R. A. Hadfield.¹

Thiessen² has investigated the hysteresis loss of iron and steel at 100° C., 20° C. and about - 70° C., the latter obtained by using solid CO₂. He found that for soft wrought iron the hysteresis increased with decreasing temperature when the maximum magnetizing field caused magnetic saturation, and that the reverse was true for low magnetizing forces. The same effects of temperature were found for annealed crescent tool steel.

¹ Jour. Iron and Steel Inst., Vol. LXVII., p. 147, 1905.

² Thiessen, PHYS. REV., Vol. VIII., p. 65.

Fleming and Dewar¹ found that the magnetic permeability of annealed soft Swedish iron decreased when cooled in liquid air for all magnetizing fields, but for the same iron unannealed they found an increase in the permeability at the low temperature. They found also no change in the hysteresis loss of a sample of soft transformer iron, for varying values of the magnetic induction, when cooled in liquid air. T. Claud² working with soft iron found a slight tendency to lower hysteresis and permeability at the lower temperature. Honda and Shimizu³ using Swedish iron, found that cooling in liquid air diminished the magnetization in low fields, but increases it in the strong, the change amounting to about two per cent. They also found that the hysteresis loss was decreased in weak inductions and increased in the strong by cooling in liquid air.

Dr. Fleming⁴ in a note to the Iron and Steel Institute, gives some further results on the magnetization of two steels (0.055 per cent. C and 0.29 per cent. C) at the temperature of liquid air. He found that the effect of low temperature on the permeability depended on the previous heat treatment. The low carbon iron, in the annealed state, gave an increase in the permeability for all fields when at the low temperature; while the high carbon steel, annealed, had its permeability decreased when in liquid air. He says: "Broadly speaking, it seems as if the result of low temperature on iron containing a large per cent. of carbon was to decrease the permeability, whilst an opposite effect was produced upon iron containing a small percentage of carbon." J. Stauber⁵ working with three steels (no analysis given), found that the lowering of temperature is accompanied by a decrease in the hysteresis loss; but that with higher magnetizing fields (30 gauss), both permeability and hysteresis loss increased with decreasing temperature.

The steels used in the following tests were made by Dr. J. A. Mathews, of the Crucible Steel Co., Syracuse, N. Y., to whom the writer wishes to express his gratitude not only for the steels, but also for the complete chemical analysis. These steels were made

¹ Fleming and Dewar, *Proc. Roy. Soc.*, Vol. 60, p. 81, 1896.

² Claud, *C. R.*, Vol. CXXIX., p. 409, 1899.

³ Honda and Shimizu, *Jour. Coll. Sc., Tokio Univ.*, Vol. XX., 1905.

⁴ Fleming, *Jour. Iron and Steel Inst.*, Vol. LXVII., p. 237, 1905.

⁵ Stauber, *Le Lumiere Elec.*, Vol. I., p. 120, 1908.

Chemical Analysis.

| Mark. | C | P | Si | Mn | S |
|-------|------|-------|------|------|------|
| P.I. | .058 | Trace | .008 | .071 | — |
| A1 | .60 | .013 | .15 | .14 | .012 |
| A2 | .74 | .012 | .16 | .14 | .013 |
| A3 | .89 | .010 | .19 | .155 | .013 |
| A4 | .98 | .012 | .16 | .15 | .013 |
| A5 | 1.18 | .012 | .14 | .14 | .013 |
| A55 | 1.26 | .012 | .16 | .17 | .014 |
| A6 | 1.37 | .011 | .19 | .16 | .012 |

by the crucible process and after being rolled were allowed to cool in the air. The composition of the different specimens is given in the preceding table.

The low carbon iron, marked P.I. in the analysis was kindly loaned the writer by Professor Bancroft, of the Department of Chemistry, Cornell University. The rods were all $\frac{5}{8}$ inch in diameter and 45 cm. in length. Previous to the magnetic tests the steels were all annealed in a platinum furnace, by heating the whole at 1000° C. for two hours and then allowing them to cool in the furnace. It is assumed that this heat treatment removed the effects of machining the steels. Unfortunately the steel marked A2 was mislaid while the magnetic tests were being made and so it was not included.

The ballistic method was used to measure the magnetic quantities. Taylor¹ has found that a heavily damped galvanometer gives more accurate results in magnetic measurements than one with small damping, because the creeping up of the induction to its final value, for any given field, takes an appreciable time. Stewart² used a voltmeter, without its series resistance, as a galvanometer for hysteresis measurements, calibrating it with a standard condenser and known E.M.F. Following this suggestion a galvanometer was made from the parts of a Weston voltmeter. The coil, wound on an aluminum form, was suspended by a fine silk fiber; the current being carried into the coil by two small spiral springs of silver. These springs were so adjusted that the silk fiber fur-

¹ Taylor, PHYS. REV., Vol. XXIII., p. 95, 1904.

² Stewart, PHYS. REV., Vol. XXI., p. 158, 1903.

nished sufficient torsion to just bring the coil to its zero position after it had been given a deflection. The galvanometer was calibrated with a standard condenser and a known E.M.F., and its constant was checked up several times during the test. This form of galvanometer proved to be very satisfactory and readings could be made quite rapidly. In making the readings it was found that in the time necessary to adjust the resistances for the following reading, the galvanometer coil would settle back to its zero and be ready for the next throw.

In order to avoid the cumulative effect of an error in any previous reading of the ballistic throw, the method of operating by steps from one extremity of the cycle, given by Ewing,¹ was used. The upper half of the hysteresis cycle was obtained in this way and the area of the plotted curve measured with a planimeter for the hysteresis loss. With each specimen three cycles were taken, both at room temperature and with the specimen in liquid air, for three values of the magnetic induction. The ballistic coil was wound on the outside of the magnetizing coil and at its center. No attempt was made to correct for the demagnetizing effect of the ends of the rods,

$$\left(\frac{\text{length}}{\text{diameter}} = 75 \right),$$

and since they all had the same length and approximately the same diameter this correction would not affect the values given when compared among themselves. A small coil was wound on the outside of the magnetization coil and a current passed through it to compensate for the effect of the earth's field in the iron. In making the tests at the low temperature the magnetizing coil and the specimen under test were placed in a long vertical Dewar tube and covered with liquid air. As the air evaporated, more was added so as to keep the coil and specimen completely and continually covered. No attempt was made to measure the temperature change which took place as the air evaporated and new air added, but the tests were never started until the violent ebullition of the air had ceased, indicating that the whole mass had reached the lowest temperature. The high temperature tests were made at

¹ Ewing, *Magnetic Induction in Iron*, p. 356, 1904 ed.

about 20° C., that of the room. In the case of the low carbon steels, since the hysteresis loss is small, several of the tests were repeated in order to make sure of the values obtained.

An inspection of the data in Table I. shows that for the lowest carbon iron the permeability, when at the temperature of liquid air is slightly higher than its value at room temperature for the highest value of the magnetic induction, and decreases for the lower values. Also, the hysteresis loss for the smallest induction has a smaller value when at the lower temperature, but at higher values of the induction the hysteresis loss is greater at the low than at room temperature. This is in agreement with the work of Honda and Shimizu¹ on a Swedish low carbon iron and Dr. Fleming² working with 0.05 per cent. carbon iron. For all the other specimens the effect of low temperature is to decrease the permeability and increase the hysteresis loss for all values of the magnetic induction studied. In order to study the change in the hysteresis loss with varying percentages of carbon, the Steinmetz³ law $W = \eta B^{1.6}$, was used, computing the value of η for the highest induction studied.

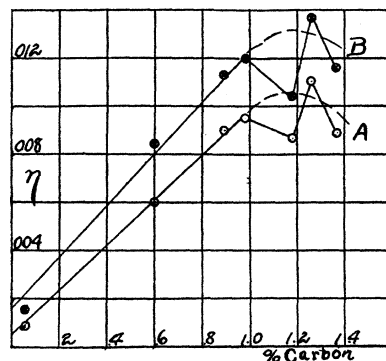


Fig. 1. Showing the relation between the hysteresis coefficient and the carbon content. Curve A represents the relation at 20° C. Curve B represents the relation at -180° C.

The curves given in Fig. 1 show the relation between the hysteresis coefficient and the percentage of carbon. It will be seen that up to .9 per cent. carbon the line has been drawn straight,

¹ Loc. cit.

² Loc. cit.

³ Steinmetz, Am. Inst. E. E. Trans., Vol. IX., 1892.

TABLE I.

| No. | Carbon. | At 20° C. | | | | | | At -180° C. | | | | | | $\Delta\eta$ in per cent. |
|-----|---------|-----------|------------|------------|-------|----------------------|--------|-------------|------------|------------|-------|----------------------|--------|---------------------------|
| | | W | B_{\max} | H_{\max} | μ | Coercive Force H_c | η | W | B_{\max} | H_{\max} | μ | Coercive Force H_c | η | |
| P1 | .058 | 5,470 | 16,950 | 51.3 | 330.3 | 0.75 | .00094 | 9,390 | 17,110 | 51.1 | 335.6 | 1.6 | .00158 | 68.4 |
| " | " | 3,741 | 14,330 | 19.8 | 723.7 | — | — | 5,809 | 14,380 | 20.6 | 698.0 | — | — | — |
| " | " | 1,839 | 8,800 | 10.0 | 880.0 | — | — | 1,500 | 8,890 | 10.8 | 814.8 | — | — | — |
| A1 | .60 | 24,250 | 13,416 | 41.7 | 321.7 | 5.1 | .00603 | 30,060 | 13,260 | 45.9 | 288.9 | 7.0 | .00838 | 39.0 |
| " | " | 18,100 | 9,048 | 18.8 | 481.3 | — | — | 20,970 | 9,048 | 25.4 | 356.2 | — | — | — |
| " | " | 4,100 | 4,420 | 9.4 | 470.2 | — | — | 5,690 | 4,400 | 10.8 | 407.4 | — | — | — |
| A3 | .89 | 27,000 | 11,150 | 36.6 | 304.7 | 8.0 | .00903 | 33,060 | 11,150 | 45.0 | 247.7 | 10.5 | .01132 | 25.3 |
| " | " | 10,518 | 6,300 | 18.5 | 340.5 | — | — | 12,464 | 6,305 | 22.6 | 278.9 | — | — | — |
| " | " | 1,283 | 1,891 | 9.1 | 207.8 | — | — | 1,283 | 1,940 | 11.1 | 174.7 | — | — | — |
| A4 | .98 | 27,120 | 10,800 | 39.0 | 276.9 | 8.5 | .00955 | 32,950 | 10,550 | 44.0 | 239.7 | 11.0 | .01204 | 26.1 |
| " | " | 10,794 | 5,976 | 20.0 | 298.8 | — | — | 12,000 | 5,810 | 24.0 | 242.1 | — | — | — |
| " | " | 1,144 | 1,577 | 9.0 | 175.2 | — | — | 1,282 | 1,618 | 11.0 | 147.0 | — | — | — |
| A5 | 1.18 | 27,360 | 11,550 | 35.7 | 323.5 | 7.5 | .00865 | 33,980 | 11,750 | 45.7 | 257.1 | 9.8 | .01045 | 20.8 |
| " | " | 10,340 | 6,900 | 18.5 | 372.9 | — | — | 12,112 | 6,858 | 22.6 | 303.4 | — | — | — |
| " | " | 1,434 | 2,478 | 9.6 | 258.1 | — | — | 1,706 | 2,433 | 11.1 | 219.2 | — | — | — |
| A55 | 1.26 | 26,040 | 9,630 | 35.7 | 269.7 | 9.3 | .01101 | 32,570 | 9,630 | 46.0 | 209.3 | 12.6 | .01378 | 25.2 |
| " | " | 7,235 | 4,326 | 16.3 | 265.4 | — | — | 9,584 | 4,320 | 21.8 | 198.2 | — | — | — |
| " | " | 1,125 | 1,440 | 8.7 | 165.5 | — | — | 1,186 | 1,440 | 11.5 | 125.2 | — | — | — |
| A6 | 1.37 | 25,410 | 10,800 | 30.9 | 349.5 | 8.0 | .00894 | 33,160 | 10,850 | 45.0 | 241.1 | 10.5 | .01158 | 29.5 |

while from that point the dotted portion indicates that the maximum is reached about 1.2 per cent. carbon, and then shows a tendency to decrease. Dillner and Enstrom¹ have shown that up to .5 per cent. carbon the relation between the hysteresis coefficient and the percentage of carbon is a straight line. A justification for the dotted portion of the curves given in Fig. 1 was found in Dr. Carl Benedicks'² classic thesis. Benedicks made a very careful study of the magnetic properties of a series of steels made in an electric furnace. The steel was studied in three states; annealed, forged and tempered.

Fig. 2 shows the curves plotted from Benedicks' data (page 150) on the steels in the annealed and forged state.

In Fig. 2 it will be seen that the curves have a very well defined maximum at about 1.32 per cent. carbon, and that the curve for the

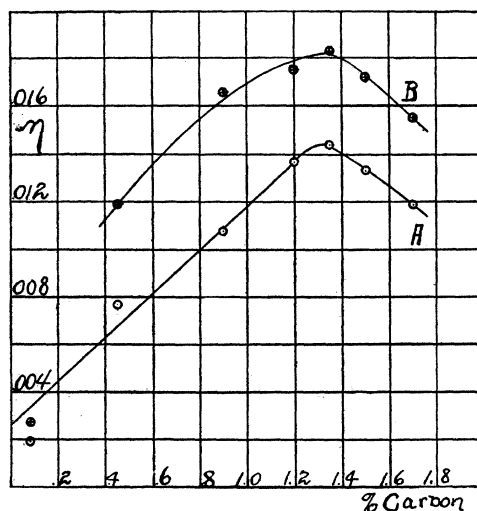


Fig. 2. Showing the relation between the hysteresis coefficient and the carbon content. Plotted from Benedicks' data. Curve A represents the relation for the steel annealed. Curve B represents the relation for the steel forged.

alloys that were forged lies above that for the annealed alloys, showing that the forging had a magnetic hardening effect on the steels.

¹ Dillner and Enström, Jour. I. & S. Inst., Vol. LXVIII., p. 408, 1905.

² Recherches Physiques et physico-chimiques sur l'acier au carbone, Carl Benedicks, Upsala, 1904.

T. Swindon¹ has studied the magnetic properties of a series of carbon tungsten steels containing a constant percentage of tungsten. The writer has taken the liberty to reproduce some of Swindon's curves, showing the relation between the hysteresis loss and the carbon content, since they seem to confirm those of Benedict's and his own.

The curves shown in Fig. 2a are taken from Swindon's paper and they show the effect of heat treatment.

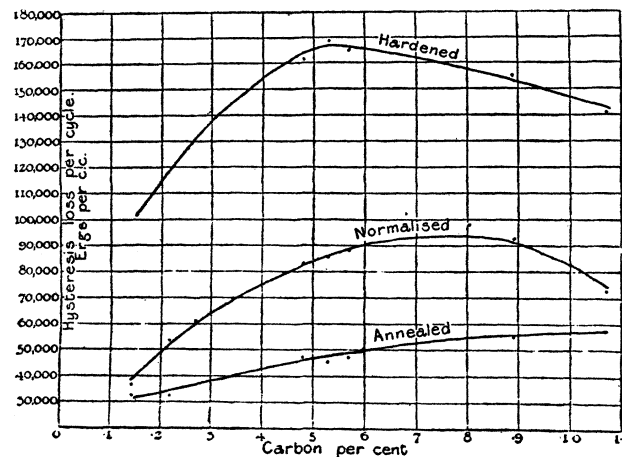


Fig. 2a. Showing the relation between the hysteresis loss and the carbon content. Taken from Swindon's paper. The "Normalizing" treatment consisted in heating to 950° C., holding that temperature for 15 minutes and then allowing the rods to cool freely in the air.

From Fig. 2a it will be seen that the curves, for the steels in the normalized and hardened conditions, resemble those in Fig. 1 and Fig. 2 in this, that the hysteresis loss reaches a decided maximum as the carbon content increases and then decreases. The position of the maximum, in the case of the tungsten steels, depends upon the degree of thermal hardening. The steels in the annealed state seem to approach a maximum at about 1.1 per cent. carbon; the series, however, does not increase sufficiently in carbon content to indicate a decrease from this maximum as the carbon increases.

Benedicks² also found the relation between the hysteresis coeffi-

¹ Swindon, *The Electrician*, Vol. LXII., pp. 830-832, 1909.

² *Loc. cit.*, p. 153.

cient (at saturation) and the coercive force to be a fixed ratio. So Fig. 3 was plotted from the data at room and liquid air temperatures. The value of the slope for the alloys at room temperature was found to be .00113; while that at liquid air temperature was .00108.

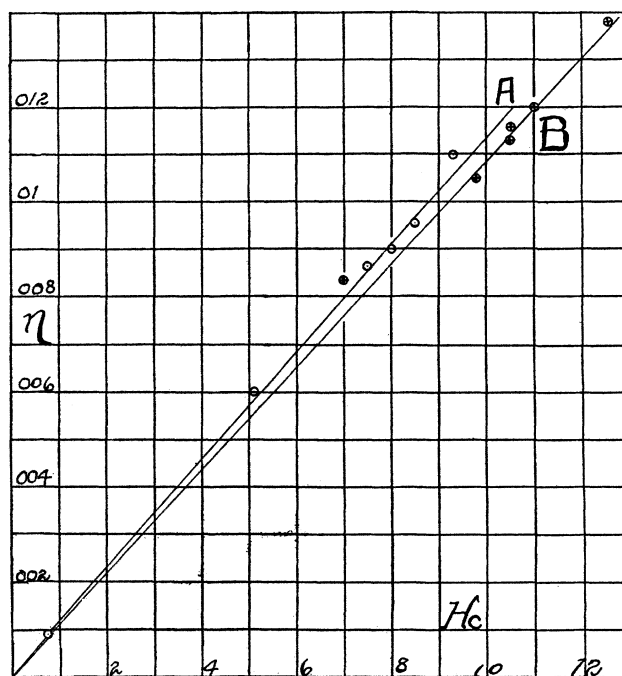


Fig. 3. Showing the relation between the hysteresis coefficient and the coercive force. Curve *A* represents the relation at 20° C. Curve *B* represents the relation at -180° C.

The tests show that the hysteresis loss at liquid air temperatures, for the higher magnetizations, was always increased; so the percentage increase in η , when the steel was at the lower temperature was computed and will be found in the column $\Delta\eta$ in per cent. The values in the column are plotted against the percentage of carbon and the curve is given in Fig. 4.

It will be seen from the curve given in Fig. 4 that the increase in hysteresis loss for a low carbon alloy is rather large and as the carbon increases this increased loss grows smaller, reaching a minimum value at about 1.1 per cent. carbon, beyond which point it again in-

creases. The resemblance should be noted between the curve (Fig. 4) with its minimum at 1.1 per cent. carbon, and the revised iron-carbon diagram given by Upton¹ with its minimum at 1 per

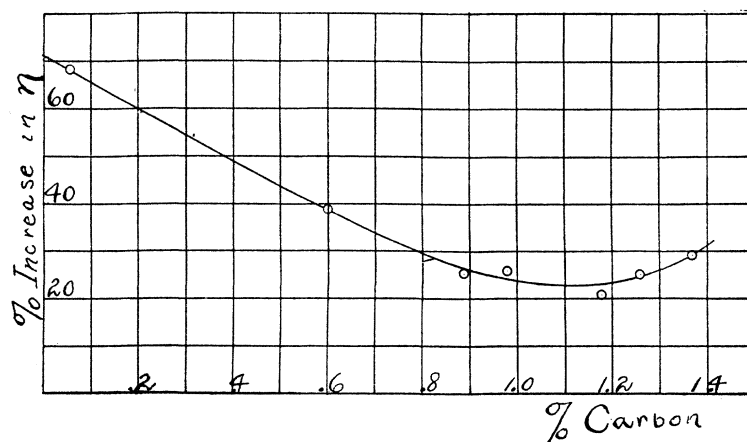


Fig. 4. Curve showing the increase (in per cent.) of the hysteresis coefficient when the steel is at the temperature of liquid air and percentage of carbon.

cent. carbon. Howe² finds that the tenacity of an iron-carbon series increases with small percentages of carbon, reaching a maximum at about 1.2 per cent. carbon and then decreasing with increased carbon. Just what bearing the iron-carbon diagram has on the curve given in Fig. 4 the writer is unable to say, for the diagram itself has been the subject of much discussion, and many changes have been proposed.

The increase in the hysteresis coefficient (in per cent.) for the forged steel over the steel in the annealed state was computed from Benedicks' ³ data and plotted in Fig. 5.

The curve given in Fig. 5 bears the same shape as that given in Fig. 4, showing a minimum value of the hysteresis coefficient at about 1.32 per cent. carbon. It should be remarked, also, that the other constituents of Benedicks' alloys, manganese, silicon, sulphur and phosphorus vary rather widely, which makes strict comparison of the two curves impossible. However it is safe to say that the

¹ Upton, J. Phys. Chem., Vol. XII., p. 507, 1908.

² Howe, Iron, Steel and Other Alloys, 1903, p. 162.

³ Loc. cit.

effect of the low temperature on the magnetic hysteresis of steel is similar to the magnetic hardening produced by forging.

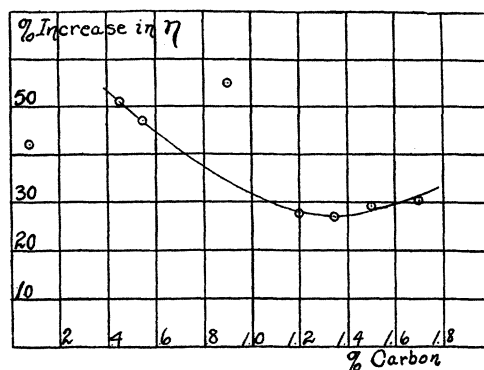


Fig. 5. Showing the carbon content and the increase in hysteresis coefficient from the annealed to forged condition.

SUMMARY.

A brief summary of the results is given below.

1. The effect of low temperature on an annealed low carbon iron is to increase both permeability and hysteresis loss in high fields, but to decrease both for very low fields.
2. For higher carbon steels, annealed, the effect of low temperature is to increase the hysteresis loss and decrease the permeability for all fields.
3. The ratio η/Hc as given by Benedicks seems to hold for steels at the temperature of liquid air as well as at room temperature.
4. The percentage increase in hysteresis loss for high fields when an annealed steel is cooled to the temperature of liquid air is a function of the carbon content. The change in the hysteresis loss decreases with the addition of carbon reaching a minimum about 1.1 per cent. carbon and then increases.
5. The change, in the hysteresis loss of a series of iron carbon alloys, produced by liquid air is analogous to the magnetic hardening of steel by forging.

THE COEFFICIENT OF LINEAR EXPANSION.

In order to determine the relation between the carbon content and the density of these steels at the temperature of liquid air, Dr.

H. G. Dorsey, of our department, kindly determined the mean coefficient of linear expansion for the steels, from room temperature down to the temperature of liquid air, by an interference method already described.¹ The results are shown in Fig. 6. From the curve it will be seen that the effect of added carbon is to decrease the expansion coefficient; and there is no indication of a change in the curve at 1.1 per cent. carbon as was found in the magnetic

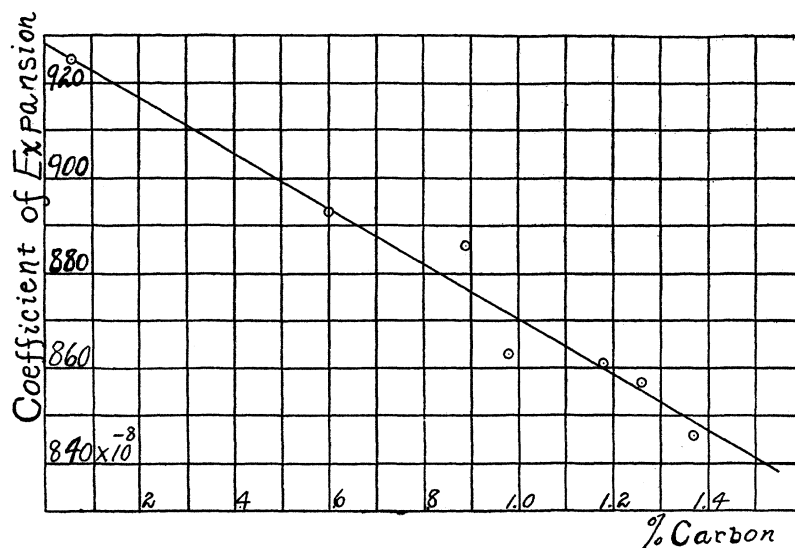


Fig. 6. Showing the relation between the expansion coefficient and carbon content.

tests. Carbonless iron, from the curve, would have a coefficient of expansion of 928×10^{-8} .

The writer hopes to add to the tests above described the specific resistance and the temperature coefficient of resistance of these steels at the temperature of liquid air.

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¹ Dorsey, PHYS. REV., Vol. 25, p. 88, 1907.