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THE HYSTERESIS OF IRON AND STEEL AT ORDINARY TEMPERATURES AND AT THE TEMPERATURE OF SOLID CARBON DIOXIDE.

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THE present article has to do with some determinations of the hysteresis of iron, steel, and nickel steel. A comparative study was made of the hysteresis of these metals at three different temperatures, one of these being the low temperature reached by means of solid CO_2, and at different values of the maximum magnetizing force. Owing to the peculiar magnetic properties of nickel steel a specimen of this metal was tested, but at only one value of the maximum induction.

The ballistic method was used both in determining curves of magnetization and in finding the losses due to hysteresis. A diagram of the apparatus used is shown in Fig. 1. *R* is the ring of the metal to be tested. *BG* is a ballistic galvanometer employed in determining the magnetic induction, and is connected with the secondary coil of the ring. *MG* is a Moler galvanometer to measure current, and is connected in circuit with the primary coil, a source of current, and a variable resistance.

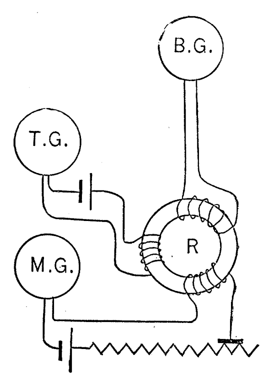

Fig. 1.

To determine the temperature of the metal a coil of copper wire was wound next to the surface of the ring. The resistance of this coil was compared with the resistance of a standard coil (kept at constant temperature) by the method of fall of potential. *TG* in the diagram represents the galvanometer used for this purpose.

Curves of hysteresis were taken with the metal at three different temperatures. Readings were first taken at the temperature of the room, or about 20° C.; then at the boiling point of water; and lastly at such low temperatures as could be obtained with solid carbon dioxide.

When the readings were taken at ordinary temperatures the ring was immersed in a bath of oil, and the temperature was thus kept constant. At the boiling point the metal ring was immersed in a vessel containing glymol, and this in turn was placed in boiling water.

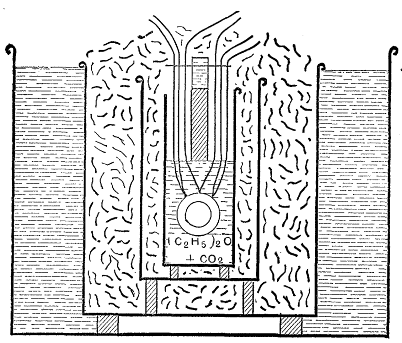

Fig. 2.

At the low temperatures the apparatus shown in Fig. 2 was used to cool the rings. As is seen in the figure it consisted of four vessels. The inner contained solid carbon dioxide and ether. A long wooden stopper was fitted tightly in this, and the terminals of the coils were led through this stopper. By means of these terminal wires the ring was suspended in the vessel. A small hole was bored in the wooden stopper to admit the ether and carbon dioxide; this was closed by a piece of cork. Around this vessel were two jackets of mineral wool, which was torn in shreds and laid lightly in. Outside of these was a jacket of ice and water. Mineral wool was then laid on top of all to insure thermal insulation.

The metal to be tested was turned in the shape of a ring with a cross section of about one square centimeter, and was about five centimeters in diameter. Four different rings were worked with, which are referred to as *A*, *B*, *C*, and *D*. *A* and *B* were from the same piece of soft wrought iron, the difference between them being that the cross section of *B* was nearly circular, while that of ring *A* was square. The results obtained were practically the same, but the data are given only for ring *A*. Ring *C* was made of crescent tool steel. Ring *D* was of 5% nickel steel. All specimens were annealed before being tested. The cross sections of *C* and *D* were rectangular, but oblong, with the longer side perpendicular to the plane of the ring. The number of turns per centimeter on the outside was thus more nearly the same as on the inside, and hence the magnetization was more uniform. This shape of the ring was also better in regard to heating or cooling.

The specimens, in all cases, were turned so that the grain of the metal ran at right angles to the plane of the ring; in the case of the figure (see Fig. 3) at right angles to the plane of the paper. The magnetization, then, if it was affected at all by the grain of the metal, was uniform throughout the ring.

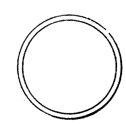

Fig. 3.

Before winding, the rings were shellacked; a layer of silk was then wrapped about the ring, and the whole was again shellacked to insure complete insulation. A layer of No. 29 copper wire was next wound upon the ring, this coil being used to measure the temperature, as described above. The secondary and primary coils were then wound, with the secondary lying between the layers of the primary. After each layer had been wound the rings were shellacked and baked.

In order to be able to immerse the rings directly in the ether and carbon dioxide they were coated with gutta that had been dissolved in carbon bisulphide, the rings being immersed in this solution and then allowed to dry; the carbon bisulphide passed off, leaving a coating of gutta upon the rings. Since ether does not appreciably act upon the gutta, the shellac was protected and all danger of short circuit was avoided. At very low temperatures, however, the gutta is brittle, and additional caution must be used to preserve the coating intact.

In taking the data for the hysteresis loops, the same maximum magnetizing force was used for all three temperatures. In the case of the wrought iron three sets, and of tool steel two sets of hysteresis loops were taken. The first set corresponds to such a maximum magnetizing force as would produce magnetization near saturation, while the second and third sets were taken with a magnetizing current of lower strength.

As already mentioned, three different specimens of metals were experimented with, iron, steel, and nickel steel. Numerical data are given in the tables at the end of this article. A graphical

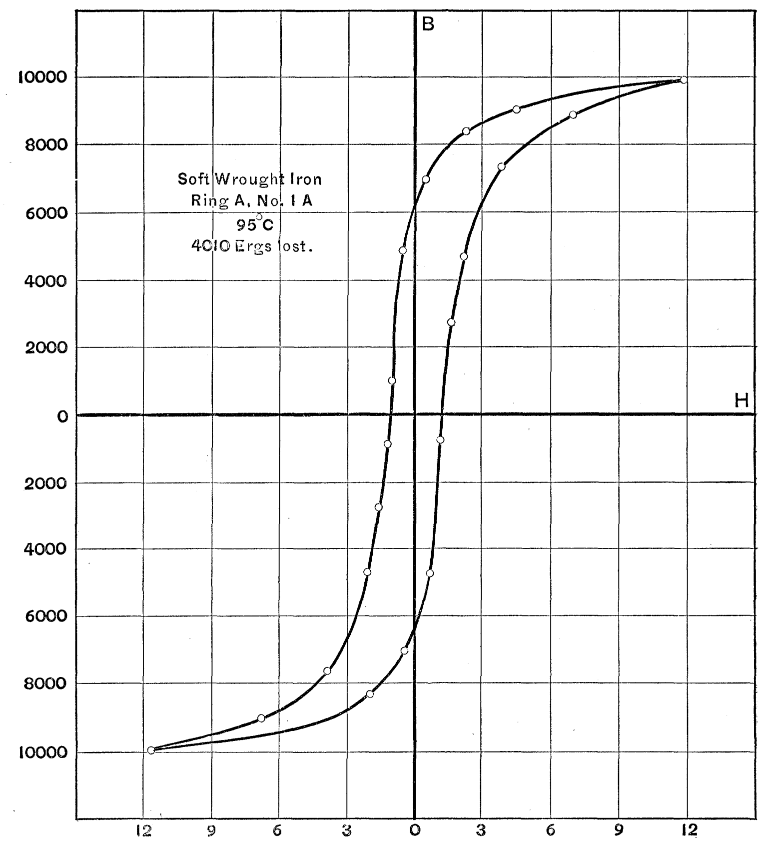

Fig. 4.

representation of the results obtained with wrought iron is shown in Figs. 4 to 7 inclusive. By comparing Fig. 4 with Fig. 5 it may be seen that the losses increase with decreasing temperatures when the maximum magnetizing current produces approximate saturation. But this is not true with low magnetizing forces, as is shown in Figs. 6 and 7. In these two cases, with such low values of H as were used, the losses *decreased* with decreasing temperatures ; *i. e.*, the behavior was just the opposite of that in the first case.

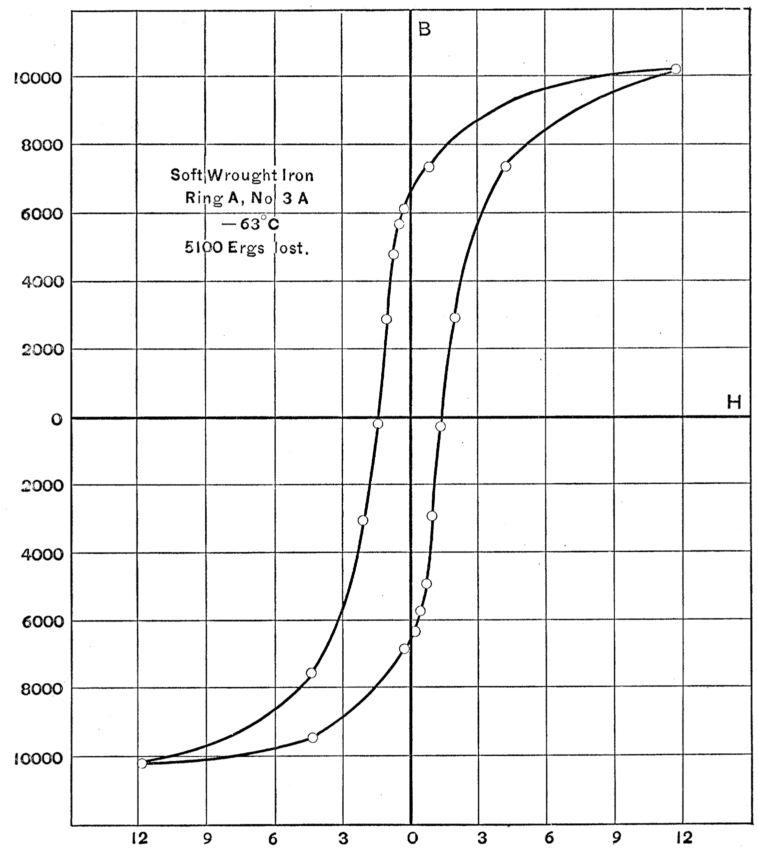

Fig. 5.

The second specimen experimented with was crescent tool steel, annealed. The results are exhibited in Figs. 8 and 9. In Fig. 8 the data were taken under circumstances analogous with those corresponding to Figs. 4 and 5 ; that is with induction near saturation. In this case, also, it is seen that the hysteresis losses increase with decreasing temperatures. With this specimen, as with the preceding one, the reverse rule is true when H is small, shown in Fig. 9.

The graphical representation of the data taken with nickel steel is shown in Fig. 10. With this specimen the same conclusions may be drawn as with the other two.

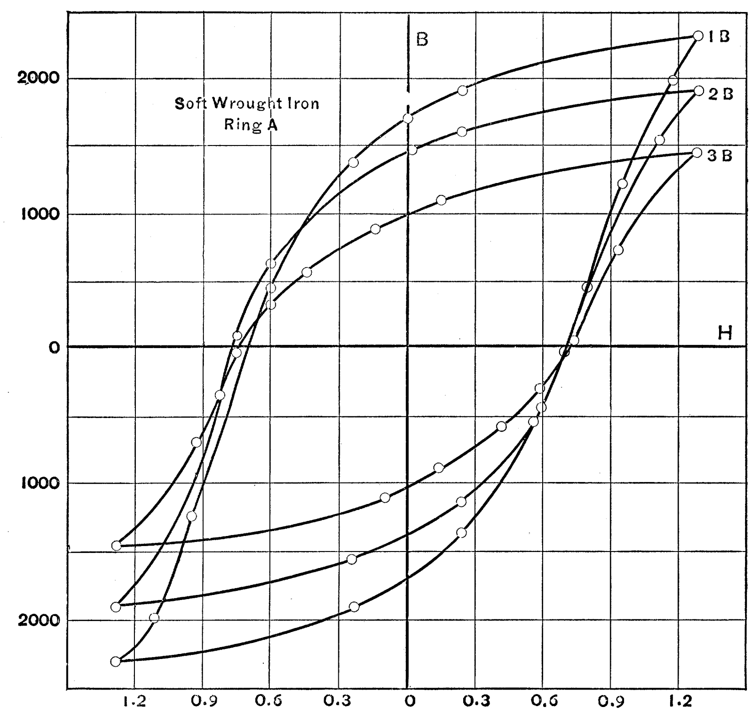

Fig. 6.

No. 1 *B*, 97°C., 433 ergs lost.
No. 2 *B*, 21°C., 371 ergs lost.
No. 3 *B*, —78°C., 266 ergs lost.

The areas of these loops were obtained with a planimeter, and the quantitative results are shown in the following tabulation:

TABLE I.

Soft Wrought Iron.					
$H=11.9$		$H=2.60.$		$H=1.30$	
Temp.	Losses, Ergs.	Temp.	Losses, Ergs.	Temp.	Losses, Ergs.
95°	4010	97°	1710	97°	430
20°	4580	22°	1610	21°	370
−63°	5100	−80°	1530	−78°	270

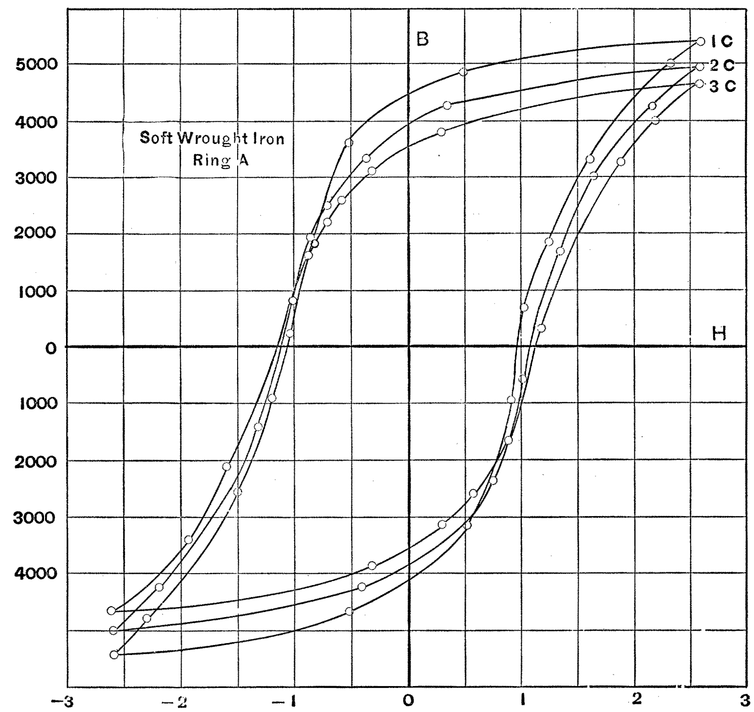

Fig. 7.

No. 1 *C*, 97°C., 1710 ergs lost.
No. 2 *C*, 22°C., 1610 ergs lost.
No. 3 *C*, −80°C., 1530 ergs lost.

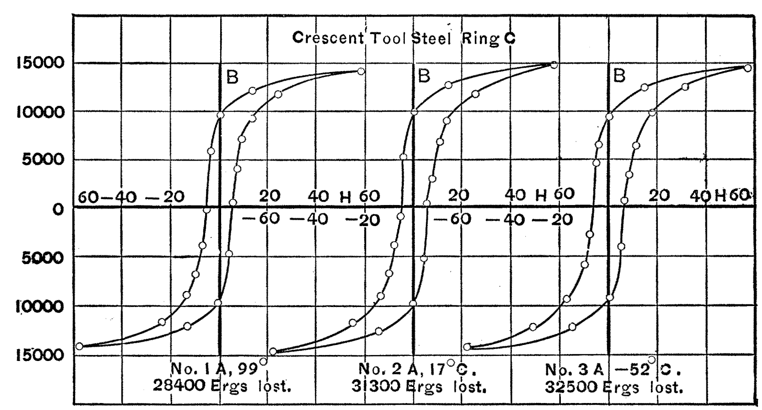

Fig. 8.

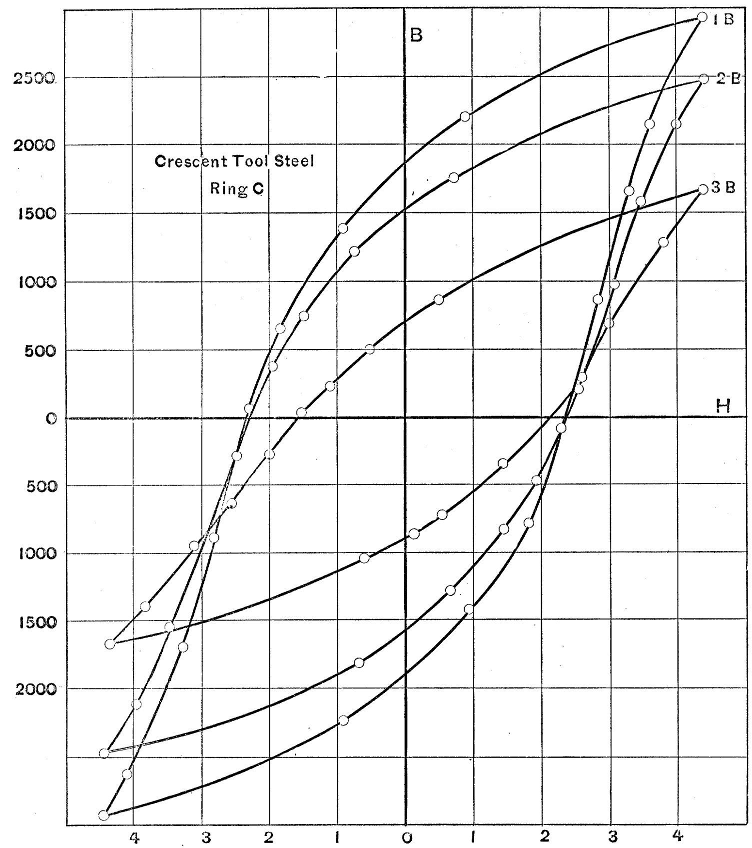

Fig. 9.

No. 1 B, 98°C., 1650 ergs lost.
No. 2 B, 18°C., 1370 ergs lost.
No. 3 B, —55°C., 690 ergs lost.

Crescent Tool Steel.				5 per cent. Nickel Steel.	
$H=57.6$		$H=4.40$		$H=52.9$	
Temp.	Losses.	Temp.	Losses.	Temp.	Losses.
99°	28400	99°	1650	99°	36600
17°	31400	18°	1380	24°	41900
−52°	32600	−55°	700	−65°	44400

The conclusions to be derived from the foregoing graphs and from the tabulation are shown graphically in Figs. 11 to 15 inclu-

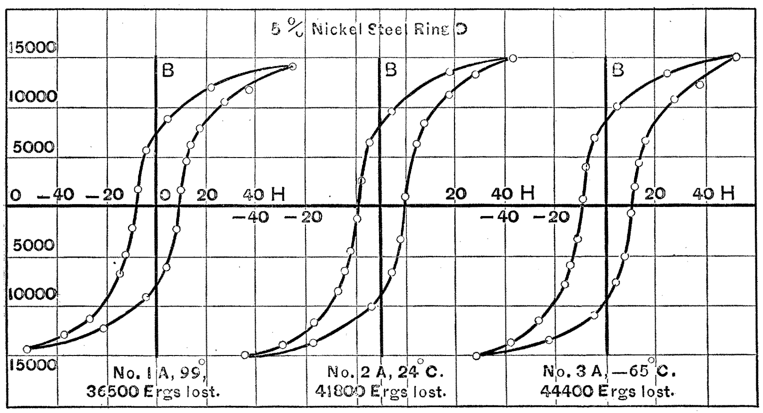

Fig. 10.

sive. They show in general that hysteresis losses increase with decreasing temperatures when the maximum magnetizing force causes approximate magnetic saturation, and that the reverse is true for low magnetizing forces.

The results of such an investigation as this are of more value if the losses at different temperatures are compared when the maximum *induction* in each case is the same. In the experiments, however, it was much more convenient to keep the maximum magnetizing *force* the same. In order to compare the losses for a given value of the maximum induction, Steinmetz's law was resorted to, viz.:

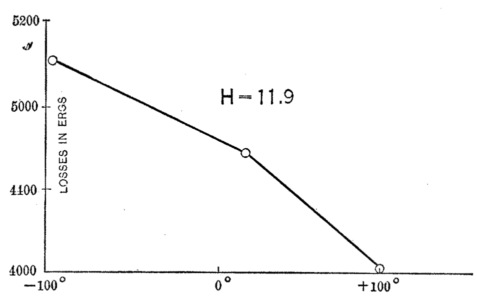

Fig. 11.
Soft wrought iron.

$$W = nB^k.$$

Where W is the hysteresis loss corresponding to a cycle whose maximum induction is B; n and k are constants for the material in question, so long as the temperature remains the same. This law was found to hold in the case of observations taken at the same temperature, and it was therefore possible to find the value of W

for a given maximum B by interpolation. The results in the case of wrought iron are given in Table II.

TABLE II.

Soft Wrought Iron. Ring A.			
Maximum Induction.	**Hysteresis Loss per Cycle.**		
B	$T = -70°$ C	$T = 20°$ C	$T = 100°$ C
2000	423 Ergs.	397 Ergs.	333 Ergs.
5000	1720 "	1620 "	1520 "
10000	5070 "	4600 '	4030 "

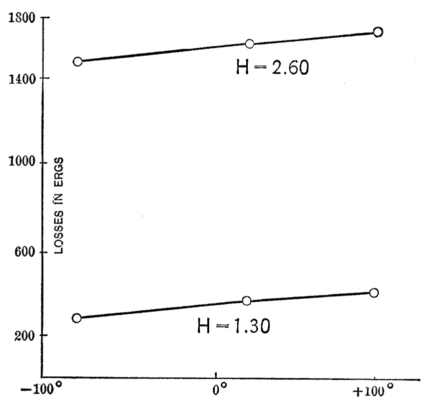

Fig. 12

Soft wrought iron.

In the case of the crescent too steel (Ring C) the hysteresis losses in ergs per cycle, *for a maximum induction of 14,700*, were found to be: 33,850, at —52°C.; 31,380, at 17°C., and 29,600, at 99°C.

With the 5% Nickel steel (Ring D) the losses per cycle, *for a maximum induction of 14,900*, were: 43,070, at —65°C.; 41,860, at 23°.5C.; 39,700, at 99°.5C.

In each o the last two cases the computations were made upon the assumption that $k = 1.6$. For the wrought iron the data were sufficient to determine the value of k at each of the three temperatures.

It will be observed that when hysteresis loops are taken in which the *maximum induction* is the same for different temperatures, the hysteresis loss is in all cases less at the higher temperatures. This result is in agreement with previous determinations of hysteresis losses at high temperatures.

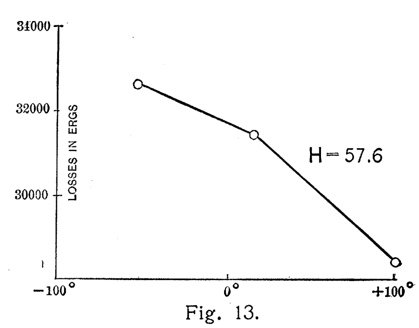

Fig. 13.

Tool steel.

It is interesting to note that the above conclusion is not in agreement with the results of Fleming and Dewar,[1] who have made an extensive series of measurements of the hysteresis losses in soft Swedish iron at ordinary temperatures and at the temperature of liquid air (— 185°C.). The method employed by these experimenters required the use of an alternating current with a frequency of 100 periods per second. No difference could be detected in the hysteresis loss per cycle, for a given maximum induction, at the two temperatures. It is to be observed that the method employed by Fleming and Dewar is susceptible of error on account of the possible presence of Foucault currents, and that its results would also be affected by a "time lag" if such were present. So far as I know the hysteresis of iron has not been investigated for the range of temperatures lying between — 80°C. and — 185°C. If the curve connecting hysteresis loss with temperature formed a maximum somewhere between — 80°C. and — 185°C. the discrepancy between the results of Fleming and Dewar and those given in the present paper would be explained.

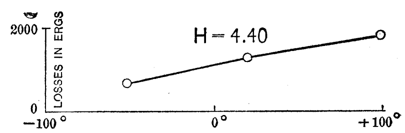

Fig. 14.

Tool steel.

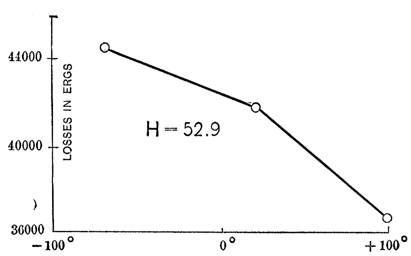

Fig. 15.

5 % Nickel steel.

Physical Laboratory of Cornell University.

[1] Proc. Roy. Soc., Vol. 60, p. 81, 1896.

TABLE III.

Soft Wrought Iron, 21° C.		Soft Wrought Iron, 95° C.		Soft Wrought Iron, −63° C.	
H	*B*	*H*	*B*	*H*	*B*
11.9	9950	11.9	9930	11.9	10200
5.5	8340	2.2	8410	1.0	7300
.5	7050	.6	7060	.2	6830
− .5	5080	− .6	4890	− .2	6130
− 1.0	1960	− 1.0	990	− .4	5680
− 1.2	− 120	− 1.2	− 930	− .7	4810
− 1.5	−1880	− 1.6	−2660	− 1.0	2680
− 2.1	−4300	− 2.3	−4880	− 1.4	− 40
− 2.9	−5950	− 3.9	−7630	− 2.1	− 3060
− 3.8	−7320	− 6.9	−9080	− 4.4	− 7570
− 6.4	−9010	−11.8	−9960	−11.8	−10200
−11.6	−9950	− 2.2	−8360	− 4.4	− 9400
− 2.2	−8410	− .6	−7010	− .2	− 6840
− .5	−6960	.6	−4720	.2	− 6400
.5	−5060	.9	− 820	.4	− 5710
.9	−1990	1.2	1200	.7	− 4900
1.2	30	1.6	2650	1.0	− 2960
1.5	1750	2.3	4750	1.4	− 70
2.2	4170	3.9	7370	2.1	2980
3.8	7140	6.9	8850	4.4	7420
6.8	8780	11.8	9870	11.9	10100
11.9	9810				

TABLE IV.

Soft Wrought Iron, 21° C.		Soft Wrought Iron, 97° C.		Soft Wrought Iron, −78° C.	
H	*B*	*H*	*B*	*H*	*B*
1.28	1920	1.29	2320	1.28	1460
.24	1610	.23	1930	.14	1110
− .24	1260	0	1710	− .14	880
− .59	640	− .23	1380	− .43	570
− .72	110	− .63	470	− .60	330
− .82	− 340	− .79	− 440	− .76	− 40
−1.10	−1500	− .83	− 650	− .93	− 710
−1.29	−1920	− .95	−1240	−1.29	−1460
− .25	−1570	−1.17	−2000	− .14	−1110
.25	−1150	−1.29	−2320	.14	− 880
.57	− 550	− .23	−1920	.44	− 560
.72	− 10	.23	−1370	.60	− 320
.82	420	.60	− 440	.74	60
1.12	1550	.79	460	.93	730
1.29	1950	.85	670	1.29	1490
		.96	1240		
		1.18	2000		
		1.30	2300		

TABLE V.

Soft Wrought Iron, 22° C.		Soft Wrought Iron, 97° C.		Soft Wrought Iron, —80° C.	
H	*B*	*H*	*B*	*H*	*B*
2.59	4980	2.59	5430	2.62	4670
.35	4250	.50	4850	.31	3830
— .35	3340	— .50	3670	— .31	3130
— .71	2500	— .86	1840	— .57	2610
— .86	1930	—1.03	270	— .71	2210
—1.01	810	—1.20	— 880	— .89	1640
—1.32	—1410	—1.51	—2540	—1.18	— 360
—1.66	—2850	—1.72	—3110	—1.54	—2080
—2.18	—4220	—2.31	—4790	—1.94	—3390
—2.58	—4990	—2.59	—5430	—2.59	—4670
— .41	—4220	— .51	—4680	— .31	—3850
.41	—3240	.51	—3160	.31	—3160
.74	—2350	.91	— 950	.58	—2620
.86	—1750	1.08	720	.88	—1660
1.01	— 560	1.25	1840	1.18	3100
1.35	1700	1.60	3310	1.52	2000
1.65	3060	1.76	3770	1.88	3330
2.17	4260	2.35	5000	2.59	4690
2.57	4880	2.64	5430		

TABLE VI.

Tool Steel, 17° C.		Tool Steel, 99° C.		Tool Steel, —52° C.	
H	*B*	*H*	*B*	*H*	*B*
58.1	14700	57.6	14280	57.9	14350
14.0	12600	12.7	12140	14.8	12320
.0	9800	0	9650	0	9480
— 4.1	5300	— 3.7	5830	— 3.5	6630
— 5.8	— 80	— 5.4	— 210	— 4.5	4665
— 8.0	— 3900	— 7.4	— 3910	— 6.6	0
—10.7	— 6900	—10.0	— 6810	— 8.3	— 2782
—14.2	— 9100	—13.1	— 8910	—11.0	— 5900
—25.0	—11900	—23.6	—11650	—17.6	-- 9560
—58.1	—14700	—57.9	—14270	—31.4	—12380
—14.1	—12600	—12.9	—12160	—57.9	—14350
0	— 9800	0	— 9640	—14.7	—12301
4.1	— 5300	3.9	— 4970	0	— 9330
5.8	40	5.4	580	4.6	— 4250
8.0	3000	7.4	4220	6.3	630
10.7	6830	8.7	7060	8.3	3310
14.1	9050	13.0	9160	11.0	6340
24.8	11900	23.6	11930	17.5	9830
58.4	14700	57.9	14550	31.4	12550
				58.3	14450

Table VII.

Tool Steel, 18° C.		Tool Steel, 99° C.		Tool Steel, —55° C.	
H	*B*	*H*	*B*	*H*	*B*
4.42	2480	4.42	2940	4.42	1680
.73	1770	.94	2230	.48	850
— .73	1220	— .94	1400	— .48	500
—1.51	760	—1.83	670	—1.10	240
—1.96	390	—2.28	60	—1.48	40
—2.60	— 250	—2.80	— 890	—2.02	— 280
—3.05	— 970	—3.28	—1700	—2.56	— 640
—3.46	—1530	—3.62	—2180	—3.08	— 970
—3.94	—2120	—4.12	—2630	—3.84	—1410
—4.42	—2480	—4.42	—2940	—4.36	—1680
— .66	—1810	— .93	—2240	— .56	—1040
.66	—1280	.93	—1420	.56	— 730
1.47	— 830	1.80	— 690	1.47	— 350
1.94	— 460	2.29	— 100	2.58	290
2.52	200	2.86	880	3.08	680
3.06	970	3.28	1670	3.84	1271
3.46	1560	3.62	2142	4.36	1655
4.03	2150	4.42	2890		
4.42	2510				

Table VIII.

Nickel Steel, 23° C.		Nickel Steel, 99° C.		Nickel Steel, —65° C.	
H	*B*	*H*	*B*	*H*	*B*
52.9	14900	52.7	14160	52.9	15180
26.8	13380	21.7	12040	21.9	13250
4.2	9730	4.2	8920	4.2	10170
— 4.2	6550	— 4.2	5750	— 4.2	7010
— 7.8	3100	— 7.6	1800	— 7.7	4240
— 9.9	— 1020	— 9.9	— 2050	— 9.9	703
—12.1	— 4320	—12.0	— 4870	—11.9	— 3020
—14.3	— 6420	—14.1	— 6630	—14.2	— 5540
—17.0	— 8330	—17.0	— 8210	—17.2	— 7770
—26.7	—11640	—26.7	—11130	—26.8	—11630
—38.4	—13500	—37.6	—12830	—38.3	—13710
—53.0	—14900	—52.9	—14160	—53.4	—15180
—26.9	—13390	—21.7	—12090	—21.6	—13230
— 4.2	— 9780	— 4.2	— 8960	— 4.1	—10510
4.2	— 6610	4.2	— 5830	4.1	— 7490
7.7	— 3140	7.7	— 1890	7.5	— 4890
9.7	900	9.9	1910	9.6	— 1415
12.0	4200	11.9	4650	11.7	2110
15.0	6330	13.9	6310	13.8	4490
17.2	8240	16.9	7890	16.6	6610
26.9	11540	26.6	10770	26.4	10383
38.0	13360	37.8	12500	38.3	12410
52.7	14730	53.0	13890	53.6	13820