



XXXVII. Electromagnets.—III. Iron and steel. New theory of magnetism

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XXXVII. *Electromagnets*.—III. *Iron and Steel. New Theory of Magnetism.* By R. H. M. BOSANQUET, *St. John's College, Oxford.*

To the Editors of the Philosophical Magazine and Journal.

GENTLEMEN,

IN the February number of the *Philosophical Magazine* (p. 73) I gave a number of experiments on the Permeability (μ) of Iron and Steel, with empirical formulæ founded on Fourier's Series. I also gave the elements of a new theory leading to equations of the form

$$\begin{aligned}\mu &= A(\mathfrak{B}_{\infty} - \mathfrak{B}) \cos \delta, \\ \delta &= f\theta, \\ \mathfrak{B} &= \frac{k}{\rho} \frac{60^\circ - \omega\theta}{\sin \theta},\end{aligned}$$

and gave the comparison of this theory with experiment in the cases of Crown (soft bar) Iron ring E, and Steel ring J (first soft state). I propose now to communicate the comparisons of all the remaining experiments of the former paper, and of three additional sets on J.

For clearness I will recapitulate shortly the bearing of the formulæ.

Each molecule has one, and only one, axis of transmission (like* a bead with a hole in it). The axis is capable of transmitting \mathfrak{B}_{∞} lines of force and no more, and the molecular permeability is proportional to $\mathfrak{B}_{\infty} - \mathfrak{B}$, or to the defect of saturation. (If we pack the hole in the bead with thin wires, the aperture remaining is represented by the number of wires that remain to be got in.)

A is the molecular permeability per unit defect of saturation.

δ is an auxiliary angle representing the obliquity of a zigzag which would augment the resistance to the amount actually observed.

θ is the average inclination of the axes of the molecules to the direction of magnetization; initially it is always 60° . ω is the unit angle.

f is the factor connecting θ and δ .

$\frac{k}{\rho}$ represents the force of molecular torsion which is in equilibrium with the tendency of the lines of force further to deflect the average molecule.

* These statements are not to be taken as actual hypotheses, but as geometrical analogies of the distribution.

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The inferences as to these constants to be drawn from the numerous experiments now discussed are not so clear as they appeared to be from the two cases treated in the last paper.

The first of the following Tables contains the constants from all the experiments that have been reduced, finishing with those obtained from Rowland's Table I.

The remaining Tables contain the detailed comparison of the theory with experiment in all the cases, except ring E, and J first soft state, which two were given in the last paper.

The last column but one of the first Table gives the product of A , the reciprocal of $\frac{\kappa}{\rho}$, and a constant. This quantity may be compared with the maximum observed value of μ in the last column.

A has been spoken of as the molecular permeability for a certain unit. Regarding magnetism as a motion or displacement, whether dynamic or static, we may thus speak of A as a coefficient of freedom within the molecule.

$\frac{\kappa}{\rho}$ being the coefficient of the forces which tend to prevent the rotation of the molecule as a whole, we may speak of its reciprocal as a coefficient of freedom without the molecule.

The last column but one may be therefore regarded as the product of coefficients of intra-molecular and extra-molecular freedom, and a constant.

This product ($c \times$ intra- \times extra-molecular freedom) is a characteristic of a given approximate state of a given piece of metal. It runs generally with the maximum of μ ; but is liable to be depressed with respect to μ where f has high values, as in the first, second, and fourth entries. As between the hard steel and the iron, the product of the coefficients of freedom is proportional to the maximum permeability.

The further general conclusions, so far as these data go, are as follows:—

In soft steel the molecular forces are chiefly extra-molecular, the freedom intra-molecular.

In hard steel the molecular forces are chiefly intra-molecular, the freedom extra-molecular.

In soft iron the average intra-molecular freedom is much greater than in hard steel, the extra-molecular freedom about the same.

In soft steel the extra-molecular freedom is much diminished, the intra-molecular freedom is moderate or high.

The distribution of the freedom between intra- and extra-molecular conditions depends minutely on the condition of the piece of iron or steel.

The variations thus arising are comparatively moderate in iron, considerable in hard steel, and enormous in soft steel.

In one or two cases the equations do not represent the values quite so well; in G two sets of constants are given.

The dimensions of the rings and details of the experiments are given in my paper of February last.

Steel ring J was examined first soft, then hard, then soft again, then hard again. Its saturation-point is taken to be 20,000 throughout. It was wound with about 4000 turns in the hard states.

P.S.—From the above conclusions we can deduce the outline of a chemical theory of the hardening and tempering of steel.

In hard steel the additional constraint, as compared with iron, is wholly intra-molecular, *i. e.* due to chemical combination with a steeling element. This combination must exist naturally at a red heat, and be stereotyped by sudden cooling.

In soft steel the intra-molecular constraint is much diminished, and the extra-molecular constraint increased. Hence in slow cooling dissociation of the steeling element takes place. This requires time. At any point in the slow cooling the condition of partial dissociation can be stereotyped by completing the cooling suddenly. This constitutes tempering.

Scheme of the Constants of the Rings.

J. Steel.—E, F, G, H, K. Soft Iron (Crown). I. Lowmoor.

Rowland's I., "Burden's Best."

Ring.	A.	$\log \frac{\kappa}{\rho}$.	$\log f$.	$\frac{A\rho}{\kappa} \times C$ $\log C = 6.1000.$	Maximum observed value of μ .
J. First soft state...	11.	4.78936	.17595	225	461
" Second soft state	.129	2.82178	.16552	245	423
" First hard state..	.01735	2.16327	.13925	150	157
" Second hard state	.0236	2.46312	.15340	102	145
E .....	.3856	2.32208	.16153	2312	2234
F .....	.189	2.01524	.16151	2297	1895
G .....	.35	2.23407	.15778	2570	2501
	.31	2.11959	.15772	2963	
H .....	.25	2.24075	.15325	1808	1797
K .....	.39	2.30682	.15973	2422	2070
I .....	.217	2.06175	.16046	2370	2173
Rowland's Table I.	.343	2.14941	.16079	2666	2472

J. First Hard State.

$$A = \cdot 01735, \quad \log \frac{\kappa}{\rho} = 2 \cdot 16327, \quad \log f = \cdot 13925.$$

$$\mathfrak{B}_{\infty} = 20,000.$$

\mathfrak{B} .	θ .	δ .	μ .		Diffs.
			Calc.	Obs.	
13	59° 56'	82° 35'	45	49	- 5
59	59 39	82 11	47	47	0
121	59 17	81 41	50	49	+ 1
170	59 0	81 18	52	50	+ 2
268	58 26	80 31	56	57	- 1
405	57 40	79 38	62	62	0
551	56 50	78 19	68	64	+ 4
645	56 20	77 38	72	67	+ 5
2189	48 40	67 4	120	115	+ 5
4492	40 8	55 18	153	150	+ 3
6496	34 39	47 45	157	157	0
8959	29 36	40 47	145	134	+11
13870	22 55	31 35	91	70	+21
16292	20 36	28 23	57	56	+ 1
19533	18 0	24 48	7	53	-45

J. Second Soft State.

$$A = \cdot 129, \quad \log \frac{\kappa}{\rho} = 2 \cdot 82178, \quad \log f = \cdot 16552.$$

$$\mathfrak{B}_{\infty} = 20,000.$$

\mathfrak{B} .	θ .	δ .	μ .		Diffs.
			Calc.	Obs.	
44	59° 56' 30"	87° 45'	101	92	+ 9
348	59 32 52	87 10	125	125	0
1110	58 35	85 46	180	188	- 8
1464	58 7	85 5	205	201	+ 4
1640	57 55	84 47	215	211	+ 4
2377	57 0	83 27	259	261	- 2
3701	55 24	81 6	325	323	+ 2
6734	52 0	76 7	411	422	-11
9957	48 43	71 19	415	423	- 8
10029	48 40	71 15	413	353	+60
13252	45 42	66 54	341	334	+ 7
14470	44 40	65 23	295	227	+68
16118	43 20	63 26	224	173	+51
19198	41 0	60 1	52	61	- 9

J. Second Hard State.

$$A = \cdot 0236, \quad \log \frac{\kappa}{\rho} = 2 \cdot 46312, \quad \log f = \cdot 15340.$$

$$\mathfrak{B}_{\infty} = 20,000.$$

\mathfrak{B} .	θ .	δ .	μ .		Diffs.
			Calc.	Obs.	
43	59° 52' 20"	85° 14'	39	39	0
204	59 33 40	84 33	44	39	+ 5
538	58 26	83 11	54	46	+ 8
821	57 36	82 0	63	58	+ 5
923	57 20	81 37	66	59	+ 7
1308	56 15	80 5	76	72	+ 4
1489	55 46	79 24	80	77	+ 3
1572	55 32	79 4	82	78	+ 4
1767	55 1	78 18	87	81	+ 6
2186	53 55	76 46	96	106	- 10
2477	53 10	75 41	102	113	- 11
3655	50 20	71 39	121	130	- 9
4305	48 50	69 31	130	133	- 3
4468	48 30	69 3	131	136	- 5
4822	47 43	67 56	134	142	- 8
5442	46 26	66 6	139	142	- 3
6255	44 50	63 50	143	143	0
7351	42 48	60 56	145	145	0
8793	40 24	57 31	142	142	0
11128	36 58	52 38	124	123	+ 1
12631	35 2	49 52	112	97	+ 15
14093	33 20	47 27	94	86	+ 8
15515	31 50	45 19	74	66	+ 8
18276	29 16	41 40	30	48	- 18

F.

$$A = \cdot 189, \quad \log \frac{\kappa}{\rho} = 2 \cdot 01524, \quad \log f = \cdot 16151.$$

$$\mathfrak{B}_{\infty} = 20,000.$$

\mathfrak{B} .	θ .	δ .	μ .		Diffs.
			Calc.	Obs.	
15	59° 52' 30"	86° 51'	208	208	0
143	58 49	85 19	306	360	- 54
513	55 40	80 45	592	587	+ 5
2784	42 0	60 55	1582	1592	- 10
3616	38 22	55 39	1747	1784	- 37
4283	35 48	51 56	1832	1869	- 37
5747	31 15	45 20	1894	1895	- 1
6438	29 27	42 43	1883	1825	+ 58
7655	26 45	38 48	1818	1704	+ 104
10767	21 40	31 26	1489	1581	- 92
12537	19 34	28 23	1241	1252	- 11
13900	18 10	26 21	1033	1000	+ 33
15035	17 11	24 55	853	692	+ 161
18834	14 31	21 3	206	150	+ 56

G.

$A=.35,$
 $\log \frac{\kappa}{\rho}=2.23407, \log f=.15778.$
 $\mathfrak{B}_{\infty}=18,000.$

$A=.31,$
 $\log \frac{\kappa}{\rho}=2.11959, \log f=.15572.$
 $\mathfrak{B}_{\infty}=18,000.$

$\mathfrak{B}.$	$\theta.$	$\delta.$	$\mu.$		Diffs.	$\mu.$		Diffs.
			Calc.	Obs.		Calc.	Obs.	
51	59 44 40	85 55	447	461	- 14	446	461	- 15
448	57 48	83 7	736	765	- 29	778	765	+ 13
1972	51 3	73 25	1601	1615	- 14	1738	1615	+123
6364	37 26	53 50	2403	2501	- 98	2423	2501	- 78
9003	33 6	47 36	2123	2241	-118	2136	2241	-105
11090	28 50	41 28	1812	1763	+ 49	1745	1763	- 18
11970	27 38	39 44	1623	1555	+ 68	1553	1555	- 2
13710	25 30	36 40	1204	1192	+ 12	1140	1192	- 52
14426	24 46	35 37	1017	832	+185	974	832	+142
15505	23 41	34 3	724	664	+ 60	680	664	+ 16
16042	23 11	31 54	562	395	+167	537	395	+142
17536	21 53	31 28	138	145	- 7	129	145	+ 16

H.

$A=.25, \log \frac{\kappa}{\rho}=2.24075, \log f=.15325.$
 $\mathfrak{B}_{\infty}=18,000.$

$\mathfrak{B}.$	$\theta.$	$\delta.$	$\mu.$		Diffs.
			Calc.	Obs.	
34	59 50	85 9	380	395	- 15
287	58 36	83 24	509	418	+ 91
1079	54 56	78 11	866	817	+ 49
6025	38 29	54 56	1727	1797	- 70
7705	34 46	49 19	1678	1717	- 39
8436	33 22	47 29	1616	1710	- 94
9740	31 6	44 16	1479	1354	+125
11261	28 50	41 2	1271	1134	+137
13355	26 10	37 14	903	885	+ 18
14501	24 55	35 28	712	630	+ 82
14718	24 40	35 1	672	502	+170
15409	24 0	34 9	536	254	+282
17642	22 0	31 18	76	97	- 21

K.

$$A = \cdot 39, \quad \log \frac{\kappa}{\rho} = 2 \cdot 30682, \quad \log f = \cdot 15973.$$

$$\mathfrak{B}_{\infty} = 15,500.$$

\mathfrak{B} .	θ .	δ .	μ .		Diffs.
			Calc.	Obs.	
67	59° 42' 45"	86° 16'	391	422	- 31
293	58 46	84 53	529	428	+101
2175	51 36	74 32	1386	1288	+ 98
2337	51 2	73 43	1439	1176	+263
3949	46 0	66 27	1800	1766	+ 34
4710	43 53	63 23	1982	1885	+ 97
5720	41 21 30	59 45	1922	2070	-148
8677	35 17	50 58	1676	1914	-238
8890	34 54	50 25	1643	1775	-132
9598	33 43	48 42	1519	1557	- 38
10413	32 27	46 52	1356	1531	-175
11511	30 52 30	44 36	1107	1104	+ 3
12148	30 1	43 22	950	799	+151
13246	28 40	41 25	659	666	- 7
13104	28 50	41 39	698	505	+193
13671	23 10	40 41	541	358	+183
15053	26 40	38 31	136	135	+ 1

I.

$$A = \cdot 217, \quad \log \frac{\kappa}{\rho} = 2 \cdot 06175, \quad \log f = \cdot 16046.$$

$$\mathfrak{B}_{\infty} = 20,000.$$

\mathfrak{B} .	θ .	δ .	μ .		Diffs.
			Calc.	Obs.	
33	59° 45' "	86° 27'	268	271	- 3
429	56 52 30	82 18	569	617	- 48
1322	51 5	73 55	1123	1024	+ 99
1624	49 20	71 23	1273	1427	-154
2395	45 15	65 29	1585	1558	+ 27
4541	36 33	52 53	2024	2072	- 48
6324	31 25	45 27	2082	2080	+ 2
6712	30 29	44 6	2071	1993	+ 78
6700	30 30	44 8	2071	2033	+ 38
7091	29 37	42 51	2054	2173	-119
8194	27 21 30	39 35	1974	1935	+ 39
9691	24 47	35 52	1813	1842	- 29
10400	23 43 30	34 20	1720	1483	+237
13159	20 20	29 25	1293	1188	+105
15050	18 32	26 49	958	818	+140
16309	17 30	25 19	724	592	+132
16939	17 0	24 36	604	444	+160
19303	14 34	21 5	141	155	- 14

Rowland's Table I.

$A = \cdot 343, \log \frac{\kappa}{\rho} = 2 \cdot 14941, \log f = \cdot 16079. \mathfrak{B}_{\infty} = 17,500.$

\mathfrak{B} .	θ .	δ .	μ .		Diffs.
			Calc.	Obs.	
71.5	59 34	86 15	391	391	0
600.5	56 27	81 44	833	869	- 36
966.7	54 27	78 51	1097	1129	- 32
2460	47 12	68 21	1903	1936	- 33
2923	45 17	65 34	2068	2078	- 10
3082	44 38	64 38	2119	2124	- 5
4959	38 15	55 23	2444	2433	+ 11
5482	36 45	53 13	2468	2470	- 2
5782	35 56	52 2	2473	2472	+ 1
6651	33 47	48 55	2445	2448	- 3
7473	31 58	46 17	2371	2367	+ 4
8943	29 8	42 11	2175	2208	- 33
10080	27 16	39 29	1964	1899	+ 65
12270	24 16	35 8	1467	1448	+ 19
12970	23 24	33 53	1290	1269	+ 21
13630	22 42	32 52	1115	1137	- 22
14540	21 45	31 30	866	824	+ 42
15770	20 37	29 51	515	462	+ 53
16270	20 12	29 15	368	354	+ 14
16600	19 49	28 42	271	258	+ 13

XXXVIII. On the Seat of the Electromotive Forces in the Voltaic Cell. By Professor OLIVER J. LODGE, D.Sc.

[Concluded from p. 280.]

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