SOME PHYSICAL PROPERTIES OF CURRENT BEARING MATTER. I. TENSILE STRENGTH. II. MELTING POINT.

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A DESCRIPTIVE résumé of the work that has been done in determining the physical properties of current bearing matter will be found in the Journal of the Franklin Institute for March 1904. The object of the present article is to present the results of some additional investigations in this matter. It may be stated at once that the results about to be presented are negative. Any change in the tensile strength of iron for a current density of 2,000 amperes per square centimeter cannot exceed one half of one per cent., and for copper, with a current density of 1,000 amperes per square centimeter, the alteration cannot exceed one fifth of one per cent. Any change in the melting point of tin for a current density of about 2,500 amperes per square centimeter can hardly exceed 2°. There is some reason to believe that a more powerful method would definitely show a small rise in the melting point.

Tensile Strength.

The substances tested were iron and copper in the form of wire. To eliminate the heating effect the wire under test was kept surrounded by a stream of cold water. Fig. 1 shows the arrangement of the apparatus. *BC* is the fine wire to be broken, stretched vertically between stronger wires in the axis of a glass tube of about two centimeters diameter. The lower end of this tube is closed by a cork *D* provided with a large hole through which one wire passes loosely on its way to a projecting support below. The upper end *A* of the tube is open, and the other wire passes out and is continued by means of a fish line over two pulleys to a pan with weights. A stream of water from the faucet is introduced at *A*, fills the tube to overflowing and escapes freely through the hole at *D*. The waste water falls into a sink over which the apparatus is set up. The temperature of the water is taken by a thermometer which hangs in the tube. When the wire to be broken carried a current this was provided by a storage cell in connection with a suitable rheostat and an ammeter reading 0.05 ampere, the terminals being loosely hooked to the wires at *A* and *D*.

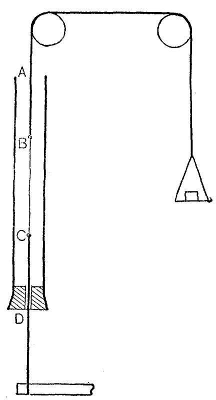

Fig. 1.

To the weights in the pan at the time of breaking is to be added a correction consisting of the weight of the pan itself minus the static friction of the cord and pulleys. The weight of the pan was nearly 100 grams, and the friction was about half a gram. As the weight in the pan was always greater than 1,000 grams, and was never increased by less than 5-gram steps, the friction was neglected and the correction considered to be an even 100 grams.

To insure that the test wire should break between the points *B*, *C*, at which it was fastened (by twisting) its middle part was slightly reduced in diameter by rubbing it with emery paper, any slight ellipticity of cross section thus introduced being allowed for by measuring the diameter in two perpendicular directions. In Tables II., III. and IV., the diameter given was measured after breaking, at the broken ends. In Table I. the diameter is that before breaking. This was obtained by measuring the diameter in three places, the thinnest part and a little on each side of it, and recording the diameter at the point nearest which the break afterward occurred, which in nearly every case was the thinnest point. This proved a somewhat unsatisfactory method, but as the result of Table I. is merely a small correction to the result of Table II., it is amply accurate for the purpose. Of course, the resulting tensile strength in Table I. would be slightly different from the corresponding value in Table II., but as comparisons are made only within each table and not between the tables this is of no moment.

Tables II. and IV. contain the results of the experiments on the tensile strength of the wire with and without a current. These experiments extended over several days, and in consequence the temperature of the tap water varied somewhat. It was therefore thought advisable to determine the effect of the variation of temperature upon the tensile strength. These results are found in Tables I. and III. As the extreme range of temperature in Tables II. and IV. is but 6°, an approximate value of the temperature coefficient is all that is necessary. To determine this the apparatus shown in Fig. 1 was slightly modified. The cork with the large hole *D* was replaced by another in which the wire fitted tightly; the water in the tube remained stationary, and was heated, when desired, by conducting into it a current of steam. It was found that the temperature coefficient for iron was negligible, but that for copper this correction could not be disregarded.

A word of explanation may be necessary concerning the mode of tabulating the results. The tensile strength of a wire is by no means uniform from point to point in the wire. To arrive at a correct idea of the average tensile strength one must break a great many short pieces and average the results. To determine the tensile strength as an end in itself it would be necessary to accumulate observations of this kind until the mean became practically constant; but this method of procedure may be shortened considerably if we desire to know only the ratio of the tensile strengths under two different conditions, such as heat and cold, current or no current. The experiments to be described were performed in this way: a spool of wire was cut into short pieces about 17 cm. long; the first, third, fifth, etc., were broken under the first set of conditions, and the second, fourth, sixth, etc., under the opposite conditions. The cumulative mean was calculated after each observation, as was also the ratio of the corresponding means. It will be seen from the tables that the ratio of the means approaches its limit more rapidly than does the mean value of the tensile strength. It is not claimed that the experiments described in Table I., have been pushed far enough to afford an accurate value of the temperature coefficient of cohesion in iron, but we may conclude from the last value in column 6 that the iron is not weakened more than about five per cent. for a rise in temperature of some 75°. We shall see that this may be neglected in the results of Table II.

By far the greatest error in the second table lies in the determination of the diameter. This was done by a micrometer caliper of 0.5 mm. pitch, graduated to hundredths of millimeters. The error in any diameter may be as much as one per cent., which would lead to an error in the area (and consequently in the tensile strength) of two per cent. The weights in the pan were added by 5-gram steps, making an error of less than one half of one per cent. The extreme range of temperature is 2.5°, by neglecting which we introduce an error of only one sixth of one per cent., according to the result of Table I. The current density is a little more than 2,000 amperes per square centimeter, and the last value in column 6 shows that any alteration of the tensile strength under a current of this intensity does not exceed one half of one per cent. Whether there is any effect less than this is doubtful ; these figures can hardly be said to establish it, considering the error of a single observation.

From the last value in column 6 of Table III., we see that copper wire is weakened about fourteen per cent. for a rise of temperature of about 76°. It is worthy of notice that the values in column 6 are practically constant after the second observation while those in column 5 have not reached their limit in eight observations.

In Table IV., the greatest error, as in Table II., is in the diameter, but is somewhat less than in the former case for two reasons: because the quantity to be measured is greater, and because each diameter here recorded is the result of four measurements instead of two, as was the case with the iron wire. The error in the tensile strength arising from this measurement is probably about one per cent. The weights in the pans were added by 10-gram steps, introducing an error of about one third of one per cent., and the tensile strength is calculated to the uniform temperature of 20°, as the greatest error that would be introduced by neglecting this correction would be about one per cent. The current density in this case is about 1,000 amperes per square centimeter.

From the last value in column 6 of this table we see that any alteration in the tensile strength under a current of this intensity does not exceed one fifth of one per cent. and from the way in which the values in column 6 fluctuate above and below unity it is altogether likely that the current produces no effect at all.

Table I.

Effect of Temperature on the Tensile Strength of Iron Wire.

1. Diameter in mm. before breaking.
2. Temperature.
3. Weight in pan at breaking; grams.
4. Tensile strength in kg. per sq. mm.
5. Successive values of the mean tensile strength.
6. Ratio of the means (hot : cold).

1	2	3	4	5	6	5	4	3	2	1
0.200	23.1	1155	39.9	39.9	0.947	37.8	37.8	1135	100.2	0.204
188	24.5	1090	42.9	41.4	0.914	37.9	37.9	1115	100.2	202
201	24.1	1165	39.8	40.9	0.958	39.1	41.7	1265	100.3	204
202	24.7	1305	43.8	41.6	0.955	39.8	41.7	1185	100.3	198
203	25.1	1150	38.6	41.0	0.976	40.0	40.9	1120	100.3	195
201	25.2	1220	41.6	41.1	0.985	40.5	43.0	1120	100.3	190
206	24.9	1285	41.4	41.1	0.973	40.0	37.3	1335	100.4	221
200	24.5	1325	45.3	41.7	0.953	40.2	41.3	1250	100.2	204

Table II.

Effect of Current on the Tensile Strength of Iron Wire.

1. Diameter in mm. after breaking.
2. Temperature.
3. Weight in the pan: grams.
4. Tensile strength in kg. per sq. mm.
5. Successive mean values of tensile strength.
6. Ratio of means (current : no current).

Current Nothing.					Current 0.7 Ampere.					
1	2	3	4	5	6	5	4	3	2	1
0.210	21.9	1253	39.1	39.1	1.11	43.3	43.3	1260	21.8	0.200
.204	21.9	1208	40.0	39.6	1.03	40.6	37.9	1237	21.9	.212
.210	21.9	1160	36.4	38.5	1.02	39.2	36.4	1150	21.9	.209
.212	21.9	1120	34.6	37.5	1.02	38.3	35.4	1150	21.9	.212
.213	21.9	1270	38.4	37.7	1.02	38.3	38.5	1245	21.9	.211
.203	22.0	1220	40.8	38.2	1.02	39.0	42.4	1245	22.0	.201
.205	22.0	1240	40.6	38.6	1.02	39.2	40.5	1275	22.1	.208
.204	22.2	1285	42.4	39.0	1.008	39.3	40.3	1205	22.7	.203
.203	22.1	1200	40.2	39.2	1.007	39.4	40.1	1210	23.0	.204
.203	23.2	1235	41.3	39.4	1.012	39.9	43.7	1300	22.6	.202
.199	22.8	1225	42.6	39.7	1.011	40.1	42.8	1300	23.3	.204
.203	24.3	1205	40.3	39.7	1.012	40.2	41.2	1245	23.4	.204
.200	23.5	1300	44.6	40.10	1.005	40.28	41.1	1230	23.3	.203
.203	23.3	1260	42.0	40.24	1.004	40.40	42.0	1245	23.7	.202
.200	23.8	1230	42.3	40.37	1.003	40.49	41.8	1240	24.0	.202
.201	24.1	1265	43.0	40.54	1.005	40.73	44.3	1335	23.8	.203

TABLE III.

Effect of Temperature on the Tensile Strength of Copper Wire.

1. Diameter in mm. after breaking.
2. Temperature.
3. Weight in pan : grams.
4. Tensile strength in kg. per sq. mm.
5. Successive mean values of tensile strength.
6. Ratio of means (hot : cold).

1	2	3	4	5	6	5	4	3	2	1
0.272	23.3	2500	44.7	44.7	0.72	32.0	32.0	2640	100.3	0.330
.365	22.7	2950	29.2	37.0	0.86	31.8	31.6	2600	100.1	.330
.307	22.5	2680	37.6	37.2	0.86	32.2	32.9	2580	100.2	.322
.308	23.7	2870	39.9	37.9	0.86	32.5	33.5	2530	100.1	.316
.324	24.1	3030	38.0	37.9	0.86	32.7	33.4	2500	100.1	.315
.322	24.7	3020	38.3	38.0	0.87	32.9	34.1	2700	100.1	.323
.310	24.5	2960	40.5	38.3	0.86	32.8	32.3	2630	100.1	.328
.315	23.4	2950	39.1	38.4	0.86	33.2	35.7	2540	100.1	.307

MELTING POINT.

The metal selected for this investigation was tin. The first method used was to immerse a thermometer directly in the molten metal. In order to get as great a current density as possible the arrangement shown in Fig. 2 was employed. The tin was melted in a hard glass test tube and a smaller tube of hard glass open at both ends was immersed in it, reaching nearly to the bottom of the melted metal. A thermometer was placed within the inner tube, its bulb being thus surrounded by a thin cylinder of molten metal which was in turn surrounded by a much larger quantity of the same substance. An iron-tipped wire coiled once around the thermometer bulb supplied the current to the inner shell of tin. The current passed down this shell, under the edge of the inner tube and out by another wire from the larger mass of melted tin outside.

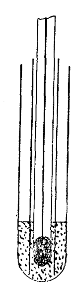

Fig. 2.

The thermometer used was one of short range (200°–250°) graduated to fifths of a degree, and read with a lens to fiftieths. Its bulb was 0.55 cm. in diameter and about the same length. The inside diameter of the inner tube was 0.75 cm., thus leaving a thin cylinder of tin whose sectional area was about 0.21 sq. cm. The current used was 3 amperes, giving a current density of about 14 amperes per sq. cm.

TABLE IV.

Effect of Current on the Tensile Strength of Copper Wire.

1. Diameter in mm. after breaking.
2. Temperature.
3. Weight in pan : grams.
4. Tensile strength in kg. per sq. mm.
5. Successive mean values of tensile strength.
6. Ratio of means (current : no current).

Current Nothing.					Current 0.8 Ampere.					
1	2	3	4	5	6	5	4	3	2	1
0.331	24.4	3100	36.9	36.9	1.008	37.2	37.2	2930	22.8	0.321
.325	22.3	2900	36.1	36.5	0.999	36.5	35.7	3000	21.4	.332
.322	21.2	3000	38.0	37.0	0.978	36.2	35.7	3000	21.6	.332
.319	21.5	2940	37.9	37.2	0.969	36.1	35.7	2850	21.3	.324
.315	21.2	2950	39.0	37.6	0.967	36.3	37.4	2950	21.1	.322
.320	21.0	2940	37.7	37.6	0.975	36.6	38.1	2820	20.8	.312
.325	20.7	2870	35.8	37.4	0.989	36.9	38.6	2910	20.7	.315
.320	20.6	2860	36.8	37.3	0.993	37.0	37.7	2950	20.5	.321
.308	25.0	2700	37.2	37.3	0.990	36.9	36.1	2860	22.3	.322
.317	21.1	2840	37.1	37.3	0.995	37.1	38.3	2930	20.8	.317
.315	20.9	2850	37.8	37.3	0.990	36.9	35.8	2930	21.0	.328
.322	22.4	3020	38.2	37.4	0.994	37.2	39.7	3010	23.1	.315
.325	22.9	2850	35.4	37.2	1.003	37.3	39.5	2900	22.8	.310
.300	21.9	2800	40.9	37.5	1.002	37.6	40.3	2700	21.5	.297
.322	21.4	2880	36.5	37.4	1.007	37.7	39.3	3010	21.2	.317
.306	21.1	2740	38.5	37.5	1.003	37.6	36.5	2680	20.9	.311
.320	19.6	2860	36.8	37.5	1.003	37.5	36.7	2990	19.2	.328
.325	19.0	3100	38.7	37.52	1.001	37.55	37.7	2970	19.3	.322
.323	19.2	3080	38.9	37.59	0.999	37.54	37.2	2700	19.0	.310
.312	19.3	2830	38.3	37.63	0.998	37.56	37.9	2800	19.4	.312

It was found by some preliminary experiments that this current in the iron-tipped wire close to the thermometer stem produced no effect on the latter. To ascertain this the thermometer bulb was immersed in water and the current was led down and up close to its stem. In the actual test the liability to such an effect would be halved, as the return current was at a little distance from the stem with the wall of the glass tube between them.

The experiments on the melting point were conducted as follows: The tin was melted and raised to about 250°, and then allowed to cool. It usually fell a variable fraction of a degree below 230°, then rose to the constant melting point, finally falling slowly as the solid metal cooled. This operation was repeated alternately with and without a current in the tin with the following results :

Melting Point.

Without Current.	With Current.
230.80	230.80
230.80	230.80
230.80	230.80

It is evident from this that the melting point of tin is not altered by as much as one fiftieth of a degree by a current density of 14 amperes per sq. cm. As the absolute melting point is unessential to this conclusion no correction was applied to the thermometer.

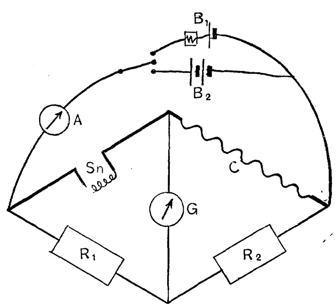

Fig. 3.

It was found impracticable to reach a very high current density by this method, and a second plan was devised. In outline, this was to use a strip of tinfoil of small cross section as one of the arms of a Wheatstones' bridge adapted to carry a current of two or three amperes, and determine the melting point of the tin by its resistance at the instant of melting. The details are shown in Fig. 3.

C, a standard one ohm coil.

A, an ammeter reading 0.05 ampere.

R_1, R_2, ordinary resistance boxes.

G, a D'Arsonval reflecting galvanometer.

B_1, a Leclanché cell with an additional resistance of 50 ohms.

B_2, two storage cells.

Sn, the tinfoil strip. To prepare this a sheet of tinfoil was cut as in Fig. 4, the narrow strip being 1 mm. wide and about 30 cm. long, while the wide parts were about 2.5 cm. wide. The wide parts were rolled up tightly to form handles for the strip, by means of which connection was made to heavy copper wires by screwconnectors. The narrow strip was wound on a small square of glass and tied on by a thread. The handles and connecting wires were vertical so that the strip on its glass plate could be hung in any desired liquid.

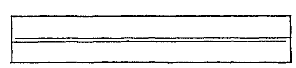
Fig. 4.

The resistance in the box R_2 was kept constantly 1000 ohms, and that in the box R_1 varied to make a balance. The resistance of the tinfoil strip was usually about one ohm when cold, so that the total resistance in the upper half of the bridge was about two ohms, while that of the lower half was a thousand times as great. Consequently, when a cell of no internal resistance, such as a storage cell, was applied to the bridge a heavy current would traverse the upper arms of the bridge and a feeble one the lower; and the current in the tinfoil strip would be very nearly equal to the current shown by the ammeter.

The standard one ohm coil was constructed of bare German silver wire 0.8 mm. diameter, used double and wound on a wooden block. It was kept immersed in kerosene, the temperature of which was noted by a thermometer. The coil was provided with short, heavy copper terminals dipping into mercury cups, which cups formed the terminal points of this arm of the bridge. The total resistance in this arm was measured against a standard correct to one part in a thousand, and was found to be 1.000 ohms at 18°. Its temperature coefficient was assumed to be 0.00044 for the few degrees that its temperature varied from 18°. It was found that the coil thus arranged would carry a current of one ampere for an hour with a rise of temperature of less than one degree.

The experiments were conducted as follows: a tinfoil strip having been put in place its resistance was measured at the room temperature in kerosene, by the feeblest current that would give a definite result. This was about 0.02 ampere, furnished by switching in the Leclanché cell B_1 with its additional resistance of 50 ohms. The temperature of the one ohm coil was noted. The strip was then hung in melted paraffin whose temperature was gradually raised with continual stirring until the tinfoil melted. As the temperature rose the resistance in R_1 was increased by one or two ohm steps to maintain the balance. The melting point of the tinfoil was indicated by a sudden throw of the galvanometer, the resistance in R_1 protecting the instrument from any excessive current. The temperature of the one ohm coil was again noted. The melted paraffin was removed, the handles scraped clean, bent toward each other and fastened by a clip, and the resistance of the connections measured.

From these data the resistance of the tinfoil strip was calculated at its melting point and at 20°. For the latter part of this calculation the temperature coefficient of tin was taken as 0.0037. We then obtain finally the ratio of the resistances of the strip at 20° and at the melting point, for a small current density.

Another strip was put in place, and the operations repeated, except that for the hot resistance the storage cells were used, sometimes in series, sometimes in parallel, according to the resistance of the strip, so as to furnish a current of about one ampere. The ratio of the resistances at the melting point and at 20° was calculated as before. As the current density was now small at 20° and great at the melting point any effect of the current on the melting point would show itself in the value of this ratio as compared with that obtained by using the weak current throughout. It was of course assumed that the resistance of tin is not a function of the current strength. While this has not been proved for the special case of tin it does not seem a dangerous assumption.[1]

The tinfoil strip was always about one millimeter wide and varied in thickness from 0.04 to 0.05 mm. Consequently the two current densities used were about 50 and 2,500 amperes per square centimeter in the thin parts of the strip. The varying thickness plays a curious part in the experiment. Its effect may be neglected for feeble currents, but for heavy currents any irregularity in thickness will reduce the apparent melting point, and the fewer the thin places the greater the apparent reduction. The thin parts, being more strongly heated by the current, will reach the melting point and break while the average temperature of the strip is below the melting point; and the fewer the thin places the lower will be this average temperature.

Experiments were made alternately with the weak and the strong current and the results are given in the following tables. A number of unrecorded experiments were made before the method was well in hand, and the experiments given are the last fifteen consecutive ones.

It will be noticed that the values in column 6 of Table V. depart less from their mean than do those of the same column in Table VI.

[1] See the résumé referred to at the beginning of this article.

TABLE V.

1. Temperature of the one ohm coil.
2. Temperature of tinfoil strip.
3. Resistance in box R_1.
4. Resistance of connections to tinfoil strip.
5. Corrected resistance of strip (for low temperatures, at 20°).
6. Ratio of resistances (hot : cold).

Current 0.02 Ampere.					Current 0.02 Ampere. Temperature, Melting.			
1	2	3	4	5	6	5	3	1
21.3	20.9	1136	0.008	1.125	1.537	1.729	1734	23.0
21.3	21.2	977	0.008	0.966	1.532	1.480	1486	22.0
20.0	18.9	1112	0.008	1.109	1.526	1.692	1698	20.1
17.6	16.7	1157	0.008	1.160	1.533	1.778	1786	18.4
20.1	19.0	843	0.008	0.840	1.549	1.301	1308	20.0
18.2	19.5	867	0.008	0.861	1.528	1.316	1324	19.4
20.3	20.0	891	0.008	0.884	1.520	1.344	1351	21.2
				Mean value	1.532			
				Average departure from mean	0.0065			

TABLE VI.

Current 0.02 Ampere.					Current 1 Ampere. Temperature, Melting.			
1	2	3	4	5	6	5	3	1
23.8	24.6	1160	0.008	1.138	1.520	1.730	1733	24.6
22.7	22.2	1437	0.008	1.423	1.526	2.171	2173	23.8
20.2	19.0	940	0.008	0.937	1.512	1.417	1424	20.4
19.0	18.7	1050	0.008	1.047	1.521	1.593	1601	19.8
19.8	19.0	831	0.008	0.826	1.553	1.283	1290	20.4
20.0	19.4	731	0.008	0.726	1.560	1.133	1140	20.3
21.9	22.9	947	0.009	0.930	1.565	1.456	1462	23.4
20.1	19.0	965	0.008	0.962	1.530	1.472	1480	19.9
				Mean value	1.536			
				Average departure from mean	0.018			

The cause is undoubtedly the higher current density in the latter case which causes the unavoidable irregularities of the strip to have a greater effect upon the result. The rise in temperature of the tinfoil increased its resistance in the ratio of 1 : 1.53, the excess of 0.53 being due to a rise of about 200°. The difference in the final means in the two tables is 4 in the third decimal place, and 4 parts in 530 for a rise of 200° would mean a difference of less than 2° in the melting point. Are we justified therefore in concluding that the melting point of tin is raised by this amount under a great current density? Undoubtedly the results of Table VI. in themselves cannot be taken as proving this, so great is the average departure from the mean; but when we recollect that the effect of great current density upon an irregular strip is always to *decrease* the apparent melting point, and when we notice that several of the values of Table VI. are greater than any of the quite concordant values of Table V., it seems likely that there may be a small rise of the melting point under a great current density which would require closer measurements to prove its existence.

It is hoped to extend this investigation to some metals of much higher melting point in the near future.

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