ART. XXI.—*On the Effect of Mechanical Hardening on the Magnetic Properties of Steel and Iron*; by LOUIS M. CHEESMAN.*

1. *Introduction.*—The relation between the magnetism and hardness of steel and iron has for many years been a subject of scientific investigation, and especially in the last few years many valuable results have been obtained in this connection.

These investigations, however, have been almost exclusively confined to the effect of the hardness brought about in steel and iron by the action of heat, while that which is caused by mechanical means has been left for the most part unconsidered. This is the more remarkable as the fact, that the mechanical hardening exerts an influence on the capacity to retain magnetism, has certainly been known for nearly a century. Coulomb,† who I believe was the first to publish this fact, says, in speaking of increasing the magnetic capacity by means of hardening, that "the hardness does not need to be accomplished by heating to redness and then suddenly cooling, but that a mechanical hardening as well causes an increase in the permanent magnetic moment."

In this connection should also be mentioned an investigation by Airy,‡ who informs us that the magnetism assumed by cold- and hot-rolled iron, under similar circumstances, are to each other as 6 is to 5. Lastly I would refer to a passage in one of Lamont's§ works, where we find it stated that the capacity of soft iron for induction is materially altered by a mechanical hardening. Thus, although the subject under consideration is by no means a new one, still little, if anything, beyond what has already been stated, seems to be known in regard to it; and I have therefore endeavored, at the instigation of Prof. F.

* Translation from Wiedemann's Annalen, vol. xv, 1882.

† Coulomb, mém. del'Acad. roy. des Sciences, p. 266. 1784. Wied. Galv., II. a, p. 341.

‡ Airy, Experiments on Iron Built Ships. Philos. Trans. 1839. Fortschr. der Physik., xix. p. 454. 1863.

§ Lamont's Handbuch des Magnetismus, p. 255.

Kohlrausch, to study the matter somewhat more systematically than hitherto has been done, with especial reference to the question, whether there are any qualitative differences between the effects of the two kinds of hardening on the magnetic properties of steel and iron.

2. *Division of the work.*—The work divides itself naturally into a consideration of the effect of the mechanical hardening: 1st, on the permanent magnetism of saturated magnets; 2d, on the temporary, as well as the permanent magnetism, by various intensities of the magnetizing force.

3. *Material.*—In regard to the material used it should be stated, that experiments were made with steel and iron from many sources. The kind of steel chiefly employed however, was that known as "English Silver Steel," which was obtained from Crooks Bros. in Sheffield and Manchester, in the form of wires, $330^{mm}$ long, with the diameters $1{\cdot}0^{mm}$, $1{\cdot}2^{mm}$ and $1{\cdot}6^{mm}$. The iron magnets were cut chiefly from a long piece of soft "Commercial Iron Wire," having a diameter of $1{\cdot}6^{mm}$.

All the material, when the contrary is not stated, was softened, before being used for the experiments, by heating it in an iron box filled in with forge scales. After the box with its contents had been at a red heat for some time the fire was allowed to die out, the material remaining in the forge until it had cooled down to the ordinary temperature. After the wires had been softened every precaution was taken to prevent any unintentioned hardening.

4. *Hardening.*—The wires were hardened either by "bending," "stretching," "hammering," or "pulling" them through holes in the well-known apparatus for reducing the diameter of wires.

The last mentioned method has the great advantage of enabling us to obtain wires of different degrees of hardness with very nearly equal diameters. Thus if three wires differing in hardness are to be obtained they may be pulled, for example, wire (a) through holes [1], [2] and [3], wire (b) through [1] and [2], and wire (c) through hole [1]; they are then softened and wire (c) pulled through [2] and [3], wire (b) through [3] and wire (a) left soft, all thus having the diameter of hole [3]. This advantage, however, is more than counterbalanced by the fact, which was evident in many ways, that the hardening is very irregular.

By far the most satisfactory experiments were made with wires hardened by "stretching" them in an apparatus [Perreaux] for determining the "breaking weight," the weight being read off by an index in kilograms.

## I.—Permanent Moment of Saturated Magnets.

The general course of the experiments here was to magnetize to saturation wires having, as far as possible in the same set of experiments, the same constitution and dimensions, but differing in their hardness; then to determine their magnetic moments.

5. *Magnetization.*—The wires were magnetized by means of a large horse-shoe magnet,* and in all cases the magnetization was repeated until the deflection on the magnetometer remained constant within at least ½ %. As great care was used to treat all wires similarly, two magnetizations were generally sufficient.

It should be stated that a series of experiments made later, the wires being magnetized by means of a coil and the current from a dynamo-electric machine, afforded results differing in no essential degree from those given here.

6. *Determination of the magnetic moment.*—The magnetic moment was determined with a small magnetometer by the Gauss deflection method, the magnets lying in such a position, west of the magnetometer, that the prolongations of their axes were perpendicular to the undeflected magnetometer needle at its middle point; the readings were taken by means of a scale and telescope.

A steel mirror, [Sauerwald, diameter $22^{mm}$] hung on a silk fiber, served as magnetometer needle.

To eliminate any unsymmetrical distribution of magnetism, as well as the zero point of the scale, the magnets were placed alternately with their north and south ends toward the magnetometer, in both positions the scale reading being taken.

The distance between the mirror and magnet was determined within $0{\cdot}15^{mm}$, and though not always the same was about $450^{mm}$; the distance between the mirror and scale was about $2000^{mm}$.

7. *Calculation of the Experiments.* — The *specific magnetism* was calculated by the following formula:

$$s=\frac{M}{m}=\frac{1}{2}\frac{r^3 T \operatorname{tg}\varphi}{1+\frac{1}{2}\frac{l^2}{r^2}}\cdot\frac{1}{m}\,\mathrm{mm}^{\frac{1}{2}}.\,\mathrm{mg}^{-\frac{1}{2}}.\,\mathrm{sec}^{-1}$$

$s$ denoting the specific magnetism,

M denoting the magnetic moment,

$m$ denoting the mass of the magnets in mgs.,

$\varphi$ denoting half the angle of deflection of the magnet,

T denoting the horizontal intensity of the earth's magnetism,

$r$ denoting the distance between the center of the magnets and the mirror in mm.,

*Horse-shoe magnet made by Funckler; portative force, 50 kg.

$l$ denoting the distance between the poles of the magnets in millimeters.

In all cases the *specific magnetism*, i. e., the magnetic moment divided by the mass of the magnet, is given, instead of the magnetic moment, so as to allow a comparison of the results obtained with magnets of different dimensions.

The value of the horizontal intensity for one point in the laboratory being known from a recent absolute determination by Professor Kohlrausch, its value for the position of the magnetometer was obtained by relative determinations.

As the results to be obtained did not possess sufficient quantitative importance to warrant an experimental determination of the distance between the poles in the case of each magnet, 0·85 of the length of the magnets was used as approximation for the quantity ($l$).

The torsion-ratio of the fiber holding the mirror was determined as 0·00027 and not taken into consideration in the calculation of the results.

## Experiments.

### 8. *Experiments with Iron.*

Set I.* Iron. Length=90 mm.

| No. | Condition. | Diameter. | Deflection in scale divisions. | Specific Magnetism. |
|---|---|---|---|---|
| 1 | Natural | 1·70mm | 22·0mm | 161 |
| 2 | Hammered | 1·71 | 27·9 | 208 |
| 3 | Stretched | 1·60 | 31·7 | 276 |
| 4 | Stretched | 1·61 | 30·8 | 253 |

* Not specially softened.

Magnets 3 and 4 were hardened by stretching, one end being held in a vice.

Set II. Iron. Length=100mm. Diameter=0·94mm.

| No. | Number of holes. | Deflection in scale divisions. | Specific magnetism. |
|---|---|---|---|
| 1 | 0 | 16·8mm | 341 |
| 2 | 1 | 25·2 | 490 |
| 3 | 2 | 26·6 | 489 |
| 4 | 3 | 26·3 | 492 |
| 5 | 4 | 28·1 | 525 |
| 6 | 5 | 25·6 | 491 |
| 7 | 6 | 27·6 | 526 |
| 8 | 6 | 29·8 | 557 |

These wires were hardened by "pulling" them through the number of holes designated in the second column, by the method more fully described under "Hardening." (See 4, above.)

SET III. IRON. LENGTH 100mm.* DIAMETER 1·67mm.

| No. | Stretching weight. | Deflection in scale divisions. | Specific magnetism. |
|---|---|---|---|
| 1 | 0 kg | 25·2 | 164 |
| 2 | 0 | 24·6 | 160 |
| 3 | 10 | 26·4 | 173 |
| 4 | 25 | 25·0 | 165 |
| 5 | 35 | 30·8 | 204 |
| 6 | 45 | 30·3 | 201 |
| 7 | 55 | 31·9 | 217 |
| 8 | 60 | 32·5 | 230 |
| 9 | 65 | 33·3 | 241 |
| 10 | 65 | 35·4 | 275 |

* The decrease of the diameter from No. 1 to No. 10 was about two per cent of the diameter of No. 1.

These wires were hardened by subjecting them to the action of a stretching force in the apparatus made by Perreaux for determining the "breaking weight" of wires.

Wire No. 1, of Set III, being subsequently hardened by "hammering," the increase in length due to the same being cut off, had after magnetization a specific magnetism of 195.

Wire No. 2, of Set III, having been bent several times and remagnetized, had a specific magnetism of 189.

Comparing I, II and III, we find in each set the smallest value of the specific magnetism in the case of the softest wire and a gradual increase of the same with the hardening, in set III the increase amounting to 70 per cent. The increase of the specific magnetism seems at times somewhat irregular; this however is easily explainable by the remarks made under the head of "Hardening."

Experiments made with a magnet of cast iron (length 102mm. diameter 7mm.) also gave an increase of the specific magnetism with the hardness, the hardening being brought about by gentle hammering.

9. *Experiments with Steel.*—In the experiments with steel a difficulty presented itself, which though also present with iron was far less annoying there, namely the fact that the different wires were not homogeneous. This was noticeable not only from the fact that wires, in as far as possible the same physical condition, could be magnetized to very different extents, but also in that their "breaking weights" differed widely. On the other hand, however, pieces cut from the same wire gave results comparable with each other.

In the following experiments a piece of each wire used was left soft for the sake of comparison.

SET IV. "ENGLISH SILVER STEEL." LENGTH 100mm. THREE WIRES.

| | | Diameter. | Deflection. | Specific mag. |
|---|---|---|---|---|
| No. 1 | *a.* Broken by a weight of 125 kgs. | 1·48mm | 51·9 | 452 |
| | *b.* Soft | 1·56 | 85·6 | 685 |
| No. 2 | *a.* Subjected to a stretching weight of 60 kgs. | 1·51 | 59·2 | 499 |
| | *b.* Soft | 1·54 | 72·2 | 580 |
| No. 3 | *a.* Subjected to a stretching weight of 30 kgs. | 1·51 | 76·5 | 621 |
| | *b.* Broken by a weight of 77 kgs. | 1·52 | 46·0 | 379 |
| No. 1 | *b.* Hammered remagnetized | | 65·5 | 524 |
| No. 2 | *b.* Hammered remagnetized | | 61·1 | 480 |

SET V.* STEEL. LENGTH 90mm.

| Wire. | Stretching weight in kg. | Diameter. | Deflection. | Specific magnetism. |
|---|---|---|---|---|
| II a | 0 | 1·28 | 61·4 | 781 |
| I a | 0 | 1·28 | 60·0 | 756 |
| III a | 0 | 1·28 | 60·1 | 769 |
| I b | 20 | 1·27 | 61·0 | 776 |
| II b | 30 | 1·29 | 61·1 | 773 |
| I c | 50 | 1·28 | 61·1 | 775 |
| III b | 55 | 1·27 | 60·2 | 774 |
| III c | 60 | 1·28 | 55·2 | 708 |
| III d | 65 | 1·26 | 48·4 | 623 |
| II c | 70 | 1·29 | 50·1 | 637 |
| I d | 75 (brach) | 1·29 | 43·7 | 556 |

* Not specially softened.

These wires were hardened as in "Set III, iron."

Comparing the results obtained with steel (sets IV and V) we find the reverse of what we saw in the case of iron, namely, that the greatest specific magnetism occurs with the softest wires.

Many experiments with both steel and iron similar to those already given were made, but as nothing was obtained from them not contained in the above they are here omitted.

10. *Influence of the ratio of the length to the thickness on the specific magnetism.*—Later results obtained with steel, though in fact corroborating the earlier experiments, seemed at first to contradict them. Hitherto I had observed in all cases with steel a decrease of the capacity to retain magnetism with the hardening; a steel bar however, having a length of 100mm. and a diameter of 7mm., gave the reverse result, its specific magnetism when soft being 100, after hardening and remagnetization 133. The possibility that the bar was iron was refuted by the hardness it assumed on being heated and suddenly cooled. Experiments were then made with bars of "English Silver Steel," from Crooks Bros., the dimensions being the same as those of the above-mentioned magnet; also in this case an increase of the specific magnetism with the hardening was observed.

Thus was proven that the increase of the magnetism in the one case and the decrease in the other did not lie in the different quality of the steel employed.

It will be observed, however, that the dimensions of the magnets used in these later experiments were very different from those of the magnets used earlier, when the magnetism was found to decrease with the hardening; in the former case the ratio of the length to the thickness being 14·3, in the latter case in the neighorhood of 65.

To ascertain whether this caused the apparently contradictory results obtained, a magnet was made of "English Silver Steel," the length being so chosen as to obtain a magnet with about the same value of $\frac{L}{D}$ as in the case of those magnets, which had shown an increase of the specific magnetism with the hardening.

The constants of the magnet were: length = 21·0mm., diameter = 1·54mm., $\frac{L}{D} = 13{\cdot}6$. The magnet showed a 30 per cent larger specific magnetism in the hard than in the soft condition.

Thus the apparently contradictory results with steel seemed to be due to the different values of the ratio $\frac{L}{D}$.

The following sets of experiments, VI, VII and VIII, were made to test this conclusion more fully.

### Set VI. "English Silver Steel."

The wires designated by (b) were hardened by a stretching weight of 70kgs.

| Wire. | Length. | $\frac{L}{D}$ | Deflection. | Specific magnetism. |
|---|---|---|---|---|
| 1 b | 21·0mm | 13·7 | 10·9 | 80 |
| 1 a | 21·0 | 14·3 | 13·3 | 102 |
| 2 b | 40·0 | 26·0 | 50·0 | 190 |
| 2 a | 40·0 | 26·7 | 62·2 | 247 |
| 3 b | 60·0 | 39·0 | 124·0 | 309 |
| 3 a | 60·0 | 40·8 | 124·1 | 338 |
| 4 b | 120·0 | 80·0 | 600·1 | 742 |
| 4 a | 120·0 | 78·4 | 428·7 | 522 |

### Set VII. From one wire of "English Silver Steel."

1b, 2b, 3b were hammered to obtain 1a, 2a, 3a.

| Wire. | Length. | $\frac{L}{D}$ | Deflection. | Specific magnetism. |
|---|---|---|---|---|
| 1 b | 31·1mm | 20·1 | 31·8 | 162 |
| 1 a | 31·3 | 20·1 | 38·5 | 186 |
| 2 b | 60·0 | 38·9 | 175·2 | 454 |
| 2 a | 61·0 | 39·1 | 176·4 | 456 |
| 3 b | 100·0 | 64·9 | 463·7 | 706 |
| 3 a | 101·0 | 65·4 | 371·9 | 566 |

SET VIII. FROM ONE WIRE OF "ENGLISH SILVER STEEL."

The wires were hardened as in set VII.

| Wire. | Length.* | $\frac{L}{D}$ | Deflection. | Specific magnetism. |
|---|---|---|---|---|
| 1 b | 27·0mm | 22·5 | 18·0 | 164 |
| 1 a | | | 19·8 | 180 |
| 2 b | 48·5 | 40·4 | 92·3 | 480 |
| 2 a | | | 93·0 | 484 |
| 3 b | 70·3 | 58·6 | 217·0 | 756 |
| 3 a | | | 173·8 | 604 |

* By mistake the increase in length due to the hammering was not measured.

The results of VI, VII and VIII, are represented graphically in fig. 1, p. 193.

From these results we see that a cylindrical magnet, magnetized to saturation, is able to retain more or less magnetism when soft than when hard, according to whether the quotient of its length by its diameter is greater or less than some value ($\alpha_0$).

Furthermore it is evident that the specific magnetism is a continuous function of the quotient $\frac{L}{D}$.

Both of the foregoing laws have already been proven for heat-hardened magnets.*

No further experiments were made to ascertain from what the value of $\frac{L}{D}$ where the curves cross ($\alpha_0$) might depend; Ruths found ($\alpha_0$) to vary between 30 and 40, while in the three cases given here it varies but little from 41.

With iron no crossing of the curves of the hard and soft magnets was observed; it is probable, however, that at greater values of $\left(\frac{L}{D}\right)$ the curves do cross, and I hope at an early opportunity to study this portion of the subject more fully.

11. *Effect of heating the hardened wires.* — The question might well be asked if, when mechanically hardened wires are softened by heating, the increase or decrease in the magnetic moment, which was coincident with the hardening, disappears. Experiments to answer this were made by softening wires, the magnetic moment of which when hard had been determined, and then remagnetizing them; the specific magnetism was found to change in each case in the direction which would be expected from the experiments given in the foregoing pages, and the magnets were capable of having their moments increased or decreased, as the case might be, by a second hardening.

* Chas. Ruths, Ueber den Magnetismus weicher Eisencylinder, Dortmund, 1876.

12. Before leaving this part of the subject the result of some experiments should be stated, which were made to ascertain what care was necessary to be taken to prevent a loss of magnetism while the magnets were being adjusted, etc. A large loss of magnetism was observed in all cases when the magnets were subjected to any sudden jarring; so that, as may be seen from the following table, great care had to be exercised between the magnetization and the determination of the magnetic moment.

| | Wire. | Falling. | Loss of original magnetism. |
|---|---|---|---|
| 1 | Steel, soft | 1·5m | 30 per cent. |
| 2 | " mechanically hard | 2·0 | 44 |
| | | 3·0 | 57 |
| 3 | " soft | 3·0 | 55 |
| 4 | " mechanically hard | 2·0 | 52 |
| 5 | Iron, " " | 2·0 | 84 |
| 6 | " " " | 3·0 | 84 |
| 7 | " soft | 2·0 | 83 |
| 8 | " " | 2·0 | 97 |
| 9 | Steel, heat-hardened | 3·0 | 6 |
| 10 | " " " | 3·0 | 4 |

As is well known the heat-hardening does much to render a magnet less sensitive to jarring, etc.; it was not discoverable, from the experiments made, that the mechanical hardening produces even in a small degree a similar effect.

## II.—Experiments with unsaturated Magnets.

13. *Apparatus.*—The apparatus was arranged as is usual in cases where the temporary magnetic moment is to be determined by the deflection of a magnetometer needle; the method having been so often described by others,* it would seem unnecessary to enter into any minute description here.

The effect of the magnetizing helix on the magnetometer was counterbalanced by a second one, the helices being placed, the one to the north, the other to the south of the instrument. The course of the current was as follows: from the battery through the two coils and a variable resistance to a key, and finally through a tangent-compass back to the battery.

By means of a commutator, the direction of the current in the tangent-compass could be reversed.

The constants of the magnetizing helix were as follows:

| | |
|---|---|
| Length | 223mm |
| Internal radius | 19 |
| External radius | 52 |
| Number of windings per layer | 55 |
| Number of layers | 10 |

As an accurate and at the same time convenient method of adjusting the magnets, a glass tube, with an internal diameter

* Compare Ruths, Ueber den Magnetismus weicher Eisencylinder. Dortmund. 1876.

somewhat larger than that of the magnets, was held firmly by corks in the axis of the coil, and the magnets pushed into position by a glass rod.

The tangent-compass was made with a single ring of copper, having a mean diameter of $404^{mm}$.

The compass needle, being but $20^{mm}$ long, was provided with a glass pointer; the scale, which was divided into degrees, was cut on mirror glass.

The order of the observations was as follows: (1.) reading of the magnetometer with the circuit open; (2.) with the circuit closed; (3.) with the circuit closed and the magnet in the coil; (4.) the deflection of the tangent-compass was then determined [commutated]; (5.) and lastly the magnetometer reading was taken with the circuit open and the magnet in the coil.

The difference between the readings (3) and (2) gives the deflection due to the temporary magnetism; that between 5 and 1, the deflection due to the permanent magnetism.

14. *Calculation of the Experiments.*—The calculation resolves itself into (a) that of the magnetic intensity in the coil, and (b) that of the resulting temporary and permanent magnetism.

(a.) *Intensity of the magnetic force.*—This resolves itself again into two, the calculation of the intensity of the current and that of the constant for the magnetic working of the coil.

The intensity of the current was calculated by the formula: $i = \mathrm{A}\ \mathrm{tg}\ \varphi$. The reduction factor $\left(\mathrm{A} = \frac{\mathrm{T}r}{2\pi n}\right)$ of the tangent-compass to the absolute system was calculated 62·7.

The correction to the above formula, due to the cross-section of the windings and the length of the needle lay within the errors of observation, and was therefore not considered.

(b.) *Intensity of the magnetic field in the coil.*

The formula,

$$\text{(I)} \qquad X_x = \frac{i\pi n}{a}\left[\frac{a-x}{\sqrt{(a-x)^2+r^2}} + \frac{a+x}{\sqrt{(a+x)^2+r^2}}\right]$$

gives the magnetic effect of a coil, of the length 2a, the radius $r$ and $n$ windings traversed by a current of intensity $i$, on a point situated in the axis of the helix at a distance from its center.

To obtain the mean intensity of the field for a bar, with the length 2b, and with a cross-section so small that we may consider the bar as lying wholly in the axis, we divide formula (I) by $2b$ and after multiplying by $dx$, integrate between the limits $x = -b$ and $x = +b$.

We thus obtain,

$$\text{(II)} \quad X_{2b} = \frac{1}{2b}\int_{x=-b}^{x=b} X_x\,dx = \frac{\pi n i}{ab}\left[\{(a+b)^2+r^2\}^{\frac{1}{2}} - \{(a-b)^2+r^2\}^{\frac{1}{2}}\right]$$

Finally to obtain the effect of the ($c$) layers of windings, the external and internal radii being respectively $r'$ and $r'$. we can multiply formula (II) by $\frac{c}{r''-r'}dr$ and integrate the product with respect to $r$, from $r=r'$ to $r=r''$. We thus obtain,

$$\text{(III)*}\quad \frac{X}{i}=\tfrac{1}{2}\frac{\pi n}{ab}\cdot\frac{c}{r''-r'}\Big[(a+b)^2.\log\frac{r''+\sqrt{(a+b)^2+r''^2}}{r'+\sqrt{(a+b)^2+r'^2}}$$

$$+(a-b)^2\log\frac{r'+\sqrt{(a-b^2)+r'^2}}{r''+\sqrt{(a-b)^2+r''^2}}+r''\{\sqrt{(a+b)^2+r''^2}$$

$$-\sqrt{(a-b)^2+r''^2}\}+r'\{\sqrt{(a-b)^2+r'^2}-\sqrt{(a+b)^2+r'^2}\}\Big]$$

The value of $\left(\frac{X}{i}\right)$ calculated by (III) for the magnetizing helix used was found to be 29·23, for $2b=100$.†

(c.) *Calculation of specific magnetism.*—In these experiments the magnets were situated so that the prolongation of the undeflected magnetometer needle was perpendicular to them at their middle point, and hence the specific magnetism is to be calculated by the following formula:

$$s=\frac{M}{m}=\left[\frac{\frac{r^3T\,\text{tg}\,\varphi}{l^2}}{1-\frac{3}{8}\frac{l^2}{r^2}}\right].\frac{1}{m}.\ \text{mm}^{\frac{5}{2}}\text{mg}^{-\frac{1}{2}}.\ \text{sec}^{-1}$$

The various quantities have the same meanings as in the corresponding formula in part I.

## 15. *Experiments.*

"English Silver Steel." Wire 1 a. Hard. Subjected to a stretching weight of 81 kgs. Length 100mm. $\frac{\text{Length}}{\text{Diameter}}=69{\cdot}0$.

| Perm. mag. Deflection. | Perm. mag. Sp. mag. | Temp. mag. Deflection. | Temp. mag. Sp. mag. | Tangent-compass Deflection. | Magnetic force. |
|---|---|---|---|---|---|
| 0·1 | 3·75 | 0·3 | 11·2 | 0°·90 | 28·8 |
| 0·8 | 29·9 | 2·4 | 89·9 | 2·55 | 81·6 |
| 1·4 | 52·4 | 4·6 | 172 | 3·55 | 114 |
| 2·8 | 105 | 6·2 | 232 | 4·50 | 144 |
| 4·8 | 180 | 10·1 | 378 | 6·45 | 207 |
| 7·8 | 292 | 16·7 | 625 | 10·65 | 345 |
| 9·8 | 376 | 26·8 | 1004 | 19·55 | 651 |
| 10·9 | 408 | 32·0 | 1202 | 31·45 | 1125 |
| 11·0 | 412 | 33·6 | 1258 | 37·55 | 1410 |

* Compare W. Weber, "Elektrodynamische Massbestimmungen, insbesondere über Diamagnetismus," p. 547. Ruths, Magnetismus weicher Eisencylinder, p. 7.

† All the magnets used were 100mm long.

WIRE 1 b. SOFT. LENGTH=100mm. $\frac{\text{LENGTH}}{\text{DIAMETER}}=67{\cdot}6$.

| Perm. mag. | | Temp. mag. | | | |
|---|---|---|---|---|---|
| Deflection. | Sp. mag. | Deflection. | Sp. mag. | Tangent-compass Deflection. | Magnetic force. |
| 0·1 | 3·66 | 1·6 | 58·6 | 1°·30 | 41·6 |
| 1·8 | 65·9 | 4·1 | 150 | 2·45 | 78·4 |
| 3·6 | 132 | 7·1 | 260 | 2·80 | 89·7 |
| 8·0 | 293 | 13·2 | 483 | 4·45 | 143 |
| 11·9 | 436 | 19·3 | 706 | 6·40 | 206 |
| 14·0 | 512 | 23·1 | 845 | 8·45 | 272 |
| 18·8 | 688 | 30·8 | 1127 | 18·20 | 603 |
| 20·0 | 732 | 34·4 | 1259 | 28·70 | 1004 |
| 20·1 | 736 | 35·4 | 1295 | 35·90 | 1327 |

"ENGLISH SILVER STEEL." WIRE 2 a. HARD (HAMMERED). LENGTH=100mm. $\frac{\text{LENGTH}}{\text{DIAMETER}}=69{\cdot}9$.

| Perm. mag. | | Temp. mag. | | | |
|---|---|---|---|---|---|
| Deflection. | Sp. mag. | Deflection. | Sp. mag. | Tangent-compass Deflection. | Magnetic force. |
| 0·7 | 24·3 | 2·2 | 76·4 | 2°·15 | 68·8 |
| 2·0 | 69·5 | 5·0 | 174 | 3·45 | 110 |
| 3·5 | 122 | 8·4 | 292 | 4·20 | 135 |
| 7·3 | 254 | 14·4 | 500 | 6·00 | 193 |
| 10·0 | 347 | 21·2 | 736 | 9·80 | 317 |
| 11·9 | 413 | 25·7 | 893 | 13·50 | 440 |
| 14·0 | 486 | 31·8 | 1105 | 23·45 | 795 |
| 15·5 | 538 | 35·9 | 1247 | 40·30 | 1554 |

WIRE 2 b. SOFT. LENGTH=100mm. $\frac{\text{LENGTH}}{\text{DIAMETER}}=70{\cdot}9$.

| Perm. mag. | | Temp. mag. | | | |
|---|---|---|---|---|---|
| Deflection. | Sp. mag. | Deflection. | Sp. mag. | Tangent-compass Deflection. | Magnetic force. |
| 0·2 | 7·10 | 1·9 | 67·5 | 1°·40 | 43·8 |
| 1·1 | 39·1 | 4·1 | 146 | 2·30 | 73·6 |
| 3·7 | 131 | 7·8 | 277 | 3·00 | 96·1 |
| 7·3 | 259 | 13·0 | 462 | 4·35 | 140 |
| 10·1 | 359 | 17·1 | 607 | 5·30 | 170 |
| 13·8 | 490 | 23·7 | 842 | 8·40 | 271 |
| 16·5 | 586 | 28·7 | 1020 | 12·95 | 422 |
| 18·2 | 647 | 32·3 | 1143 | 18·05 | 597 |
| 19·9 | 707 | 35·5 | 1260 | 28·05 | 977 |
| 19·8 | 703 | 36·9 | 1310 | 35·70 | 1318 |

"ENGLISH SILVER STEEL." BAR 3 a. HARD (HAMMERED). LENGTH=101·5mm. $\frac{\text{LENGTH}}{\text{DIAMETER}}=14{\cdot}5$.

| Perm. mag. | | | |
|---|---|---|---|
| Deflection. | Sp. mag. | Tangent-compass deflection. | Magnetic force. |
| 1·0 | 1·61 | 1°·35 | 43·2 |
| 3·5 | 5·62 | 3·10 | 99·3 |
| 5·1 | 8·19 | 4·45 | 143 |
| 9·3 | 13·9 | 6·90 | 222 |
| 13·1 | 21·0 | 9·60 | 310 |
| 20·3 | 32·6 | 14·20 | 464 |
| 33·3 | 53·5 | 33·50 | 1103 |
| 35·5 | 57·0 | 37·65 | 1416 |

"ENGLISH SILVER STEEL." BAR 3 b. SOFT. LENGTH=100mm. $\frac{\text{LENGTH}}{\text{DIAMETER}}=14{\cdot}3$.

| Perm. mag. | | Tangent-compass deflection. | Magnetic force. |
|---|---|---|---|
| Deflection. | Sp. mag. | | |
| 3·2 | 5·10 | 2°·25 | 72·0 |
| 4·9 | 7·81 | 3·30 | 106 |
| 6·9 | 11·0 | 4·30 | 138 |
| 9·0 | 14·3 | 5·50 | 177 |
| 12·6 | 20·1 | 8·50 | 274 |
| 18·0 | 28·7 | 12·85 | 418 |
| 23·1 | 36·8 | 17·85 | 590 |
| 32·2 | 51·3 | 31·90 | 1140 |
| 34·3 | 54·1 | 38·45 | 1450 |

IRON. WIRE 4 a. HARD ("PULLED"). LENGTH=100mm. $\frac{\text{LENGTH}}{\text{DIAMETER}}=139$.

| Perm. mag. | | Temp. mag. | | Tangent-compass deflection. | Magnetic force. |
|---|---|---|---|---|---|
| Deflection. | Sp. mag. | Deflection. | Sp. mag. | | |
| 0 | 0·0 | 0·7 | 91·9 | 1°·85 | 59·1 |
| 0·2 | 26·3 | 1·6 | 110 | 2·10 | 67·2 |
| 4·1 | 539 | 5·9 | 775 | 4·20 | 135 |
| 5·1 | 670 | 7·2 | 946 | 5·40 | 173 |
| 5·9 | 775 | 9·2 | 1208 | 8·35 | 269 |
| 6·3 | 827 | 12·5 | 1642 | 18·10 | 599 |

IRON. WIRE 4 b. SOFT. LENGTH=100mm. $\frac{\text{LENGTH}}{\text{DIAMETER}}=139$.

| Perm. mag. | | Temp. mag. | | Tangent-compass deflection. | Magnetic force. |
|---|---|---|---|---|---|
| Deflection. | Sp. mag. | Deflection. | Sp. mag. | | |
| 1·8 | 245 | 2·8 | 380 | 1°·25 | 40·0 |
| 2·7 | 367 | 4·0 | 543 | 1·45 | 46·4 |
| 3·8 | 516 | 5·9 | 801 | 1·90 | 60·8 |
| 4·2 | 570 | 8·8 | 1195 | 4·15 | 133·0 |
| 4·3 | 584 | 9·9 | 1344 | 5·60 | 179·7 |
| 4·3 | 584 | 11·4 | 1548 | 13·60 | 443 |
| 4·3 | 584 | 11·8 | 1603 | 19·55 | 651 |

The results are graphically represented in figs. 2 and 3 on the following page.

16. *Conclusions.*—If we compare the curves (Fig. II), representing the temporary specific magnetism of steel and iron as dependent on the magnetizing force, we see, as was to be expected, that the mechanical hardening to some extent hinders the turning of the molecules by the magnetic force. From the curves (Fig. I), representing the permanent specific magnetism of steel we see, that, where the quotient $\left(\frac{L}{D}\right)$ is greater than $(\alpha_0)$, the softer magnet has the advantage, without reference to the intensity of the magnetizing force. If on the other hand $\left(\frac{L}{D}\right)$ is less than $(\alpha_0)$ (Fig. III), the softer magnet has the advantage up to a certain value of the magnetizing force, when the specific magnetism of the harder magnet overtakes that of the softer, and is ahead at the saturation point, as we saw in the first part of this article.

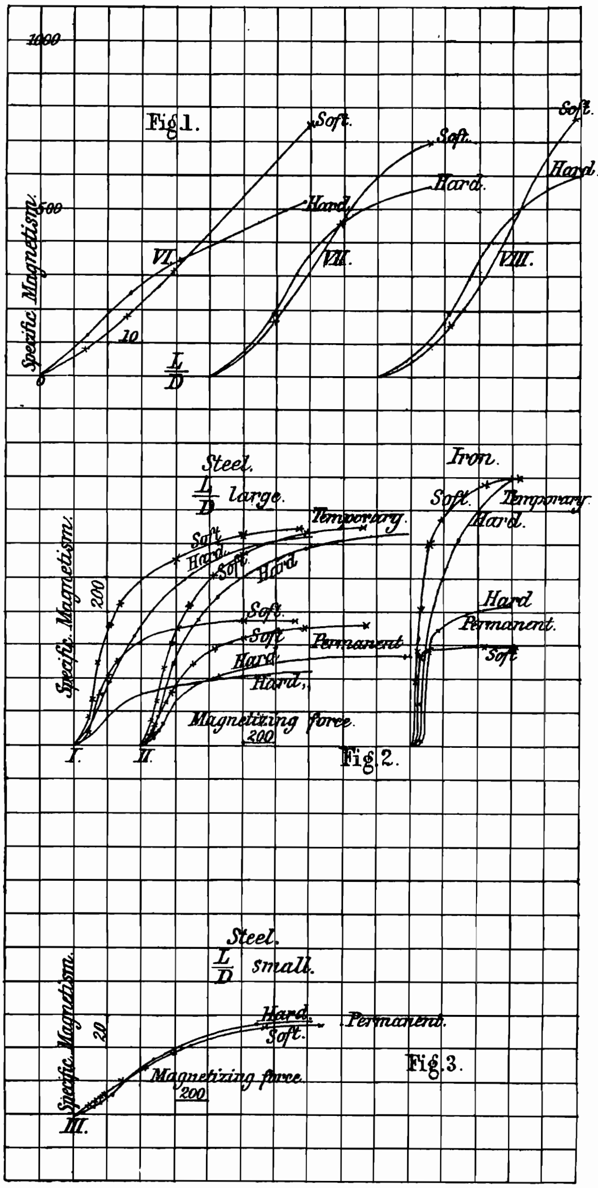
Fig. 1.
1000
500
Specific Magnetism.
10
L/D
Soft.
Hard.
VI.
VII.
VIII.
Steel.
L/D large.
Iron.
Temporary.
Soft.
Hard.
Permanent.
Specific Magnetism.
200
Magnetizing force.
I.
II.
Fig. 2.
Steel.
L/D small.
Permanent.
Specific Magnetism.
20
Magnetizing force.
III.
Fig. 3.

The same holds for the permanent specific magnetism of iron,* as for steel where $\left(\frac{L}{D}\right)$ is less than $\alpha_0$. These results are in entire accordance, qualitatively, with the results obtained by Ruths† and others with heat hardened magnets.

*Differences between the mechanical and heat hardening.*—We have thus seen that both mechanical and heat hardening bring about changes in steel and iron, which, for the most part, affect their magnetic properties similarly, and the question naturally arises whether there is any reason for believing the conditions caused by each to differ, other than in degree.

A comparison of their effects on some of the physical properties of steel would seem to require an affirmative answer.

Thus the specific resistance of steel has been shown to be very materially altered by the heat hardening, a change of 200 per cent taking place at times,‡ while the specific resistance of steel wires hardened by "pulling" is thereby altered, at the most, a few per cent.

Thus also, if we consider the change of specific gravity by hardening and that of the corresponding specific magnetism, we are led to believe the two conditions to be different; steel, if heat hardened, has the smallest specific gravity§ when hardest and the largest specific magnetism [pre-supposing $\frac{L}{D}$ small], so that the largest specific magnetism corresponds to the smallest value of the specific gravity; when steel is hardened by hammering, on the other hand, the specific magnetism $\left[\frac{L}{D}\text{small}\right]$ and specific gravity increase together, as I have repeatedly found by experiment.

It would seem also to follow from the foregoing that the magnetic moment is not dependent on the specific gravity, as at times has been supposed.‖

Physical Institute. University of Würzburg, Nov. 1, 1881.

*Compare remarks at end of paragraph 10.

†Chas. Ruths. Ueber den Magnetismus weicher Eisencylinder. Dortmund, 1876.

‡ Compare Strauhal and Barus, Ueber Anlassen des Stahles und Messung seines Härtezustandes, Wied. Ann., vol. xi, p. 976. 1880.

§Carl. Fromme, Wied. Ann., vol. viii, p. 352. 1879.

‖Compare the remarks of Ruths on this point, p. 48.