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LI. *Change of the Modulus of Elasticity of Ferromagnetic Substances by Magnetization.* By K. HONDA, *Rigakushi*, S. SHIMIZU, *Rigakushi*, and S. KUSAKABE, *Rigakushi* *.

IT has been generally admitted that magnetization has very little effect upon the elasticity of ferromagnetic substances. Wertheim† first measured with a micrometer the elongation of an iron wire due to tension in the magnetized and in the unmagnetized state with exactly the same result. Guillemin‡ placed an iron bar horizontally and fixed it at one end and hung a small weight at the other, which was left free. The magnetization of the bar by a coaxial coil produced a small rise of the weight. Wartmann§ used Chladni's figures to investigate the change of elasticity of magnetized iron and steel plates, and also examined the sound accompanying longitudinal and transversal vibrations of magnetized iron wires. No influence of magnetization was observed. Trèves|| set in vibration two tuning-forks having the same period of vibrations. When one of them was placed in a coil and magnetized by a strong electric current, its vibration was accelerated producing beats; but when the current was broken the beats were no more to be heard, and the two notes were in unison. This experiment shows an increase of the modulus of elasticity by magnetization. H. Tomlinson¶ found, on the contrary, that the elongation of an iron wire by loading is independent of magnetization. Bock** found the effect to be smaller than $\frac{1}{2}$ per cent., if there is any. By passing an electric current through a stretched pianoforte-wire, M. G. Noyes†† noticed an increase of elasticity, which was less than 1 per cent. Maurain‡‡ also found a small increase of elasticity by means of tuning-forks placed in a very strong magnetic field. In the investigation on the effect of tension upon magnetic elongation of a pianoforte-wire, B. Brackett§§ observed a small increase

* Communicated by Prof. Nagaoka.

† Wertheim, *Ann. de Chim. et de Phys.* [3] xii. p. 610 (1842).

‡ Guillemin, *Comp. Rend.* xxii. pp. 246, 432 (1846).

§ Wartmann, *Ann. de Chim. et de Phys.* xxiv. p. 360 (1848).

|| Trèves, *Comp. Rend* lxvii. p. 321 (1868); *Archives des Sci. Nat.* n. s. xxxiii. p. 74 (1868).

¶ Tomlinson, *Proc. Roy. Soc.* xl. p. 447 (1886).

** Bock, *Wied. Ann.* liv. p. 442 (1895); *Phil. Mag.* [5] xxxix. p. 548 (1895).

†† M. G. Noyes, *Phys. Rev.* [4] ii. p. 277 (1895); *Phys. Rev.* [6] iii. p. 432 (1896).

‡‡ Maurain, *Comp. Rend.* cxxi. p. 248 (1895).

§§ B. Brackett, *Phys. Rev.* [5] v. p. 257 (1897).

of elasticity amounting to about $\frac{1}{2}$ per cent. J. S. Stevens and H. G. Dorsey* used the method of flexure, and applied the interference-fringes to measure the amount of depression. The effect of magnetization upon a loaded iron and steel bar was found to be very small; it showed a minute increase of the modulus of elasticity by about $\frac{1}{300}$ per cent. for the strongest current used. In the next year, Stevens measured the magnetic elongation of steel wires under several loadings and found an increase of elasticity. Lately, Tang† published his results on the same subject. He made use of the principle that the moment of a bifilar suspension increases with tension applied to its lower end. Besides iron, he also examined nickel wires. In fields ranging from 200 to 480 c.g.s. units the maximum increase of the modulus of elasticity amounted to about 1 per cent. for iron and nickel.

All of these experiments show that magnetization increases slightly the modulus of elasticity in iron and nickel, and that the change increases with magnetizing force, but its law is not clearly brought out.

2. The method of measurement in our experiment was similar to that of Stevens and Dorsey, as shown in fig. 1.

Fig. 1.

A and B are two magnetizing coils of the same dimensions, which rested horizontally in a coaxial line. FG is a stout brass rod of rectangular section extending between two fulcrums; it is also supported at the middle point by another fulcrum. The coils can therefore be moved independently of the bar. LM is a rod to be tested placed in the axial line

* J. S. Stevens and H. G. Dorsey, *Phys. Rev.* [2] ix. p. 116 (1899); *Phys. Rev.* [2] xi. p. 95 (1900); *Zeitschr.* ii. p. 682 (1900).

† Tang, *Ann. de Phys.* vi. p. 34 (1901).

of the coils. It is supported at L and M by two fulcrums; one of them is an ordinary wedge fixed to the brass rod, while the other consists of a cylinder which can rotate about its own axis. Q is the weight suspended from the middle of the bar. At the centre of the bar a fine copper wire, whose diameter is about 0.08 mm., is soldered and stretched vertically upwards by means of a weak spring P. This copper wire is wound once round a rotating cylinder to which a reflecting mirror is fixed, and stretched upwards, as used in Hertz's dynamometer. The rotation of the cylinder is observed by means of a vertical scale and a telescope.

The dimensions of each part of our arrangement are as follows:—

Length of each coil	=	39.90 cm.
Its internal diameter.....	=	5.80 cm.
$4\pi n$	=	393.5 cm.
Distance between the coils in } air-gap	=	2.5 cm. for iron and steel. 2.0 cm. for nickel and cobalt.
Distance between two fulcrums } L and M	=	59.91 cm. for iron and steel. 21.95 cm. for nickel and cobalt.
Diameter of rotating cylinder ...	=	0.172 cm.
Scale-distance	=	261.3 cm.

The sensibility of our apparatus was such that a displacement of one division of the image of the vertical scale in the field of the telescope corresponded to the change of depression of 1.72×10^{-5} cm. at the middle of our ferromagnetic rod. It was necessary to protect the mirror and the thin copper wire from air-currents in order to get rid of minute vibrations of the mirror.

The measurement was conducted in the following way. The bar to be tested was placed in the axial line of the coils and then loaded by a weight. The tension of the fine copper wire was then suitably adjusted, and the mirror was directed to the observing telescope. This adjustment was performed as in the former experiment. To begin with, the bar was demagnetized and then the initial reading taken. A current was then passed through the coils and the corresponding deflexion noted. These processes were repeated with successively increasing currents.

Since the resistance of the coils did not exceed 3 ohms, no trace of heating effect due to current was observed during the time in which the deflexion was taken; we therefore dispensed with a water-jacketing arrangement. The lateral contraction or elongation, which necessarily accompanies the magnetization of a ferromagnetic rod, was at most of the order 2×10^{-6} cm. for iron and 7×10^{-6} cm. for nickel. Hence with our arrangement, the lateral change of dimension

due to magnetization was within the limit of experimental errors. The disturbance of the results due to magnetic elongation or contraction in the longitudinal direction was eliminated by means of the rotating cylinder which served as one of the fulcrums.

The bar bent slightly downwards if loaded; hence when it was magnetized it would strive to make itself straight. This may cause an apparent increase of elasticity; but it was confirmed by direct experiments that the effect was negligibly small, because the reading obtained by inclining two coils with respect to the bar to a degree greater than the actual case was almost the same as in the case when the coils rested in a coaxial line.

Since the bar was considerably shorter than the whole length of the coils, it lay nearly in a uniform field except at the middle. The effect of the air-gap between the coils was also studied, varying its width by 1 or 2 cms.; however, such a change had no sensible effect on our results.

3. The dimensions of the specimens used in our experiments and their moduli of elasticity were as follows:—

Metals:	Soft Iron.	Steel.	Wolfram Steel.	Nickel.	Cobalt.
Length	64.00 cm.	64.00 cm.	64.00 cm.	24.20 cm.	27.30 cm.
Breadth	0.903	0.920	0.948	0.510	Radius
Thickness ...	0.901	0.913	0.953	0.511	=0.680
Elasticity ...	2.02×10^{12}	2.01×10^{12}	2.05×10^{12}	1.96×10^{12}	1.79×10^{12}

The present arrangement was not suitable for the absolute measurement of the modulus of elasticity, since the yielding effect of several parts of the arrangement disturbs the result. Hence the modulus of elasticity was determined by the ordinary method of flexure with two reflecting mirrors.

The intensity of magnetization of the specimens was determined by the magnetometric method. The results are given in fig. 2. Ordinates represent the intensity of magnetization, and abscissæ the effective field.

The magnetic change of length was found to have an intimate relation to the change of elasticity, so that it was measured for each specimen. To each end of the bar a brass rod of the same thickness and 15 cms. long was soldered. The bar was then vertically suspended coaxial with the magnetizing coil by means of a screw adjustment. From its lower end a weight of 1 or $\frac{1}{2}$ kilogram was hung by a

Elasticity of Ferromagnetic Substances by Magnetization. 463

copper wire. The weight was dipped in water so as to avoid its vibratory disturbance. The rotating cylinder with a

Fig. 2.

reflecting mirror, described in the preceding paper, was brought in contact with the copper wire under slight pressure to prevent sliding. The magnetizing coil was so long that the bar lay in a nearly uniform field. The results of experiment are given in fig. 3. Here H denotes effective field

Fig. 3.

and $\frac{\delta l}{l}$ the magnetic change of length per cm. We observe that the elasticity of a substance undergoing a large change of length is also similarly affected by magnetization.

4. *Soft Iron*.—In observing the deflexion from our scale-reading by passing a current through the coils, we were first struck with the large effect contrary to the results of previous experimenters. The largest deflexions for soft iron and Wolfram steel amounted to about 9 cm. with a scale at 2.61 m. distant in a field of 500 c.g.s. units, while for a steel bar it was only one third. Even nickel, for which the distance between the two fulcrums was only 22 cm., showed a deflexion of 3 cm.

The curves for the change of depression corresponding to different loadings in soft iron are given in fig. 4. Ordinates

Fig. 4.

represent in centimetres the amount of the change of depression, taken positive when it indicates an increase of elasticity, and taken negative when it indicates a decrease. Abscissæ represent the effective field, and T the suspended weight in grams.

The general course of these curves resembles that of magnetization. In weak fields, however, we notice a minute decrease of elasticity when the load exceeds about 1.5 kilograms. Iron contracts laterally when magnetized by weak currents, and this contraction may produce such an apparent decrease of elasticity; but the actual calculation shows that the initial depression is more than can be accounted for by the lateral contraction.

When the field increases beyond this region, the change of depression increases rapidly and soon reaches its asymptotic value, after which the increase takes place quite slowly. As the weight is increased the change of depression is also increased. The rate of increase is large with small loading and decreases as the load is increased, approaching to an asymptotic value.

From the change of depression we may calculate the ratio of the change of elasticity to the modulus itself. The depression due to the suspended weight as well as to its own weight in an unmagnetized bar is given by the approximate formula *

$$d = \frac{l^3 g}{4 E a b^3} (T + \frac{5}{8} W),$$

where l , a , b are the length, breadth, and thickness of the bar, T and W the suspended weight and the weight of the bar itself respectively. d and W refer to the part of the bar lying between two fulcrums. The observed change of depression divided by this depression is the ratio in question,

that is, $\frac{\delta E}{E}$. Some of the results of our calculation are given in the following table. In the calculation the effect of the weak spring stretching the thin copper wire was corrected for.

$H/T + \frac{5}{8}W$.	329 gr.	829 gr.	1349 gr.	1849 gr.	5869 gr.
20	1.64×10^{-2}	0.77×10^{-2}	0.50×10^{-2}	0.47×10^{-2}	0.44×10^{-2}
30	2.79	1.47	1.09	1.08	0.88
50	3.15	1.84	1.35	1.28	1.16
100	3.36	1.92	1.48	1.37	1.28
250	3.40	1.93	1.51	1.40	1.32
400	3.40	1.93	1.51	1.40	1.32

These numbers show that the value of $\frac{\delta E}{E}$ becomes greater as the field is increased, and that it becomes less as the weight is increased.

Fig. 5.

5. *Steel*.—The general character of the change of depression is similar to that of soft iron, as given in fig. 5; but the

* Clebsch's *Elasticität*, p. 375; Winkelmann's *Physik*, i. p. 266.

466 K. Honda, S. Shimizu, and S. Kusakabe on Change of initial decrease is not observed. Some of the values of $\frac{\delta E}{E}$ are given in the following table:—

$H/T + \frac{5}{8}W$.	1251 gr.	2184 gr.	3096 gr.
50	0.14×10^{-2}	0.15×10^{-2}	0.17×10^{-2}
100	0.22	0.25	0.25
200	0.27	0.33	0.31
300	0.28	0.37	0.35
400	0.30	0.40	0.39

This steel bar shows a comparatively small increase of elasticity. With the present specimen, the value of $\frac{\delta E}{E}$ under a given field reaches a maximum with a load lying between 1270 and 2200 grams.

6. *Wolfram Steel*.—The change of depression for Wolfram steel bar by magnetization is similar to that for soft iron, as shown in fig. 6. It is still greater, and the curve does not

Fig. 6.

tend to become asymptotic. The initial decrease of elasticity is more marked in the metal than in soft iron and occurs even with the smallest load. The following table contains the values of $\frac{\delta E}{E}$ for different fields and loadings:—

$H/T + \frac{5}{8}W$.	358 gr.	797 gr.	1378 gr.	2206 gr.
70	1.79×10^{-2}	1.88×10^{-2}	1.67×10^{-2}	1.56×10^{-2}
100	2.05	2.02	1.79	1.64
200	2.55	2.27	2.00	1.80
300	2.93	2.42	2.10	1.89
400	3.26	2.60	2.18	1.92
500	3.54	2.68	2.23	1.97

The above table shows that the increase of elasticity under a given field becomes generally less as the load is increased. In weak fields, however, a maximum is observed as in the case of steel. It also increases first rapidly and then slowly as the field is increased.

7. *Nickel*.—Nickel rod shows an abnormal behaviour as regards the change of elasticity by magnetization. The

Fig. 7.

results of observation are graphically shown in fig. 7, and the values of $\frac{\delta E}{E}$ are given in the following table:—

$H/T + \frac{1}{2}W.$	105 gr.	287 gr.	561 gr.	832 gr.
30	-1.80×10^{-2}	-1.60×10^{-2}	-1.30×10^{-2}	-1.08×10^{-2}
70	-4.08	-1.40	-0.70	-0.38
100	-3.84	-0.92	-0.21	+0.30
200	-2.50	+0.46	+1.20	+1.80
300	-0.88	+1.47	+2.07	+2.52
400	+0.42	+2.17	+2.56	+2.83
500	+1.34	+2.67	+2.84	+3.03

Thus the modulus of elasticity considerably decreases in weak fields and increases in the strong. The field of no change decreases as the load is increased. In a given field the amount of decrease becomes less as the load is increased; in strong fields, however, the increase becomes gradually greater as the load is increased.

Fig. 8.

8. *Cobalt*.—Our cobalt bar was too thick and the maximum deflexion in the field of the telescope was only 1.5 divisions,

so that we cannot claim for cobalt the same accuracy as in iron, steel, and nickel. But we notice a distinct increase of elasticity, as shown in fig. 8 and the following table :—

H / T.	1005 gr.	2830 gr.
100	0.24×10^{-2}	0.08×10^{-2}
200	0.48	0.22
300	0.59	0.33
400	0.70	0.39

The total depression d due to a suspended weight T is calculated by the formula, neglecting the weight of the bar itself,

$$d = \frac{1}{12\pi} \frac{Tl^3}{ER^4},$$

where R is the radius of the bar.

Generally speaking, the above results for iron, steel, and nickel are far greater than those given by former experimenters. That the modulus of elasticity of nickel decreases in weak fields has not yet been observed. Moreover, no experiment has ever been tried with cobalt.

We have to express our cordial thanks to Profs. H. Nagaoka and A. Tanakadate for valuable suggestions in carrying out the present experiments.

LII. *On the Velocity of Reaction before Complete Equilibrium and the Point of Transition are reached, &c.*—Part III.
By MEYER WILDERMAN, *Ph.D., B.Sc. (Oxon.)* *.

CONTENTS.

- I. The general laws concerning all kinds of equilibrium in heterogeneous systems, and velocity of reaction before any one of them.
- II. The true meaning of the equations for chemical equilibrium in heterogeneous systems. The laws of chemical velocity of reaction in heterogeneous systems.
- III. On the real and apparent points of chemical equilibrium in heterogeneous systems.

I. *General Laws.*

WE now pass to the determination of the general laws which concern all three kinds of equilibrium in heterogeneous systems and the velocity of reaction before any one of the three kinds is reached.

* Communicated by the Author.