



XXXVII. Change of length of ferromagnetic wires under constant tension by magnetization

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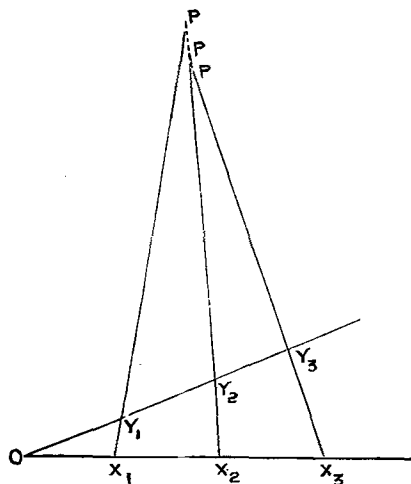
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The fact that Ramsay and Young's formula is deducible from Rankine's shortened formula is indicated by Ayrton and Perry in a paper to the Physical Society*, in which

Fig. 2.



the accuracy of Rankine's complete formula is strongly insisted on.

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XXXVII. *Change of Length of Ferromagnetic Wires under Constant Tension by Magnetization.* By K. HONDA, Riga-kushi, and S. SHIMIZU, Rigakushi†.

1. **I**N his earliest systematic experiments on the change of length by magnetization of iron and steel rods, Joule‡ noticed that the effect of tension is to diminish the elongation, and that if the tension exceeds a certain limit the magnetization causes contraction instead of elongation. Repeating the same experiment, S. Bidwell§ made special investigation on this point, and confirmed Joule's results. Besides iron he examined nickel wire; the magnetic contraction of the wire is decreased by tension in weak fields, but it is increased in strong. These changes also increase with

* Phil. Mag. [5] xxi. p. 255; Proc. Phys. Soc. vii. p. 372 (1886).

† Communicated by Prof. Nagaoka.

‡ Joule, *Phil. Mag.* xxx. pp. 76, 225 (1847).

§ Bidwell, Proc. Roy. Soc. xl. p. 109 (1885); tom. cit. p. 257 (1886);
ibid. xlvii. p. 469 (1890); Ewing's Magnetic Induction, p. 240.

tension. B. Brackett*, G. Klingenberg†, K. Tangl‡, have also investigated the same subject, and obtained results similar to those of Bidwell.

In Bidwell's experiment, which is generally regarded as the most reliable, the wire to be tested carried the magnetizing coil with it, so that even the smallest tension was greater than 3 kilog. per square millimetre. Hence the effect of small loading, which is remarkable in nickel, was not well studied. The sensibility of his apparatus cannot, moreover, be considered as sufficiently delicate at the present day. It was, therefore, thought desirable to repeat his experiment with an arrangement giving higher accuracy. Besides iron and nickel we also examined nickel-steels kindly placed at our disposal by Dr. Ch. Ed. Guillaume, which showed a remarkable anomaly with regard to the change of length and of volume.

2. The apparatus used in the present experiment is in principle the same as that of Prof. Nagaoka. The chief difference consists in using a rotating cylinder§ to cause a reflecting mirror to turn through a minute angle, instead of three-pivots system.

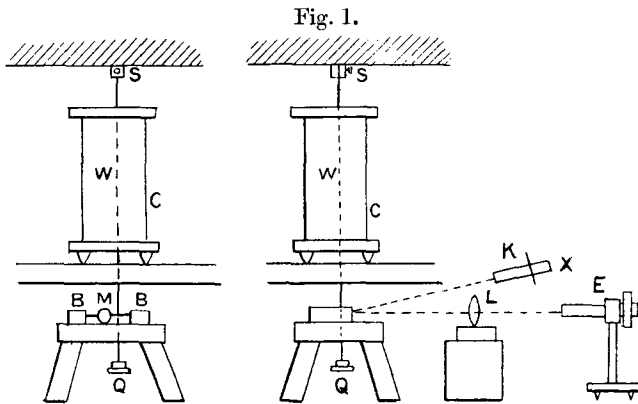


Fig. 1 shows the front and side views of the apparatus. C is the magnetizing coil and W the wire to be tested, whose upper end is clamped to the support S, while its lower end carries a weight Q. M is a reflecting mirror fixed to the

* Brackett, *Phys. Rev.* v. (5) p. 275 (1897).

† Klingenberg, *Inaug. Diss.*, Berlin, 1897; *Beibl.* xxi. p. 897 (1897); *Inaug. Diss.*, Rostock, 1899; *Beibl.* xxiii. p. 270 (1899).

§ K. Tangl, *Ann. der Phys.* vi. p. 34 (1901).

|| Hertz, *Instrumentenkunde*, iii. p. 17 (1883); *Gesammelte Werke*, Bd. i. p. 227.

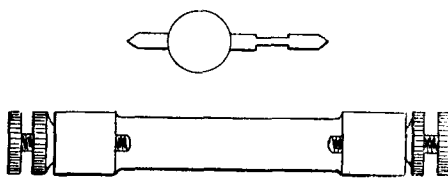
rotating cylinder, the ends of which terminate in cones and fit in the agate cups fixed on the heads of screws in the brass socket BB. K is a collimator, L a lens, and E a micrometer with ocular scale. The slit of the collimator is illuminated by a gas-flame; the light leaves the collimator adjusted for a parallel beam, and is reflected by the mirror M, and converges in the micrometer field through the lens L. In the middle of the slit a very fine glass fibre is stretched parallel to the edge, the image of which is clearly seen in the micrometer. The vertical wire touches the rotating cylinder under a suitable pressure; if the wire elongates or contracts the mirror rotates through a small angle, and the corresponding displacement of the image of the fibre is observed in the micrometer field.

The magnetizing coil is 30 cm. long and gives a field of 37.97 c.g.s. units at the centre by passing a current of one ampere. The wire to be tested is soldered into well annealed soft copper wires of about the same diameter, as shown in fig. 2. It is hung vertically in the axial line of the magnetizing coil so as to lie in a nearly uniform field. The pan

Fig. 2.



Fig. 3.



attached to the lower end of the wire carries in its under face a few pieces of cotton which softly touch a wooden stand for the purpose of damping, without producing sensible pressure. The forms of the rotating cylinder and the brass socket are drawn in fig. 3.

The stand on which the brass socket is fixed can be made to move up and down as well as forward and backward by means of screws. By this arrangement the cylinder can be

made to touch the vertically suspended wire with suitable pressure, and a small rotation of the mirror given at our disposal. This arrangement is omitted in the above figures. The rotating cylinder is made of steel and is 1.51 mm. thick, and the sensibility of our apparatus is such that one division of the micrometer ocular corresponds to a change of length of 2.72×10^{-7} per cm. of the ferromagnetic wire.

3. The method of observation was as follows:—The wire to be tested was hung vertically and stretched by a weight of 5 kilograms for three or four hours to make it straight. To begin with, all the weights were removed, and then the wire was again loaded with $\frac{1}{2}$ or 1 kilogram. The wire was then completely demagnetized, and magnetized by passing gradually increasing currents, and the corresponding deflexions were taken, the demagnetization being effected before each magnetization. A set of observations being thus taken, successively increasing loadings were applied and the corresponding sets of observations noted.

Since the resistance of the magnetizing coil was only 0.6 Ω the thermal expansion of the ferromagnetic wire due to the magnetizing current was negligibly small for the currents used in the present experiments. The electromagnetic action between the steel cylinder and the coil was also found to be negligibly small. When the pressure in the contact surface between the cylinder and the wire was moderate repeated applications and removals of the magnetizing field showed no trace of slipping on the cylinder.

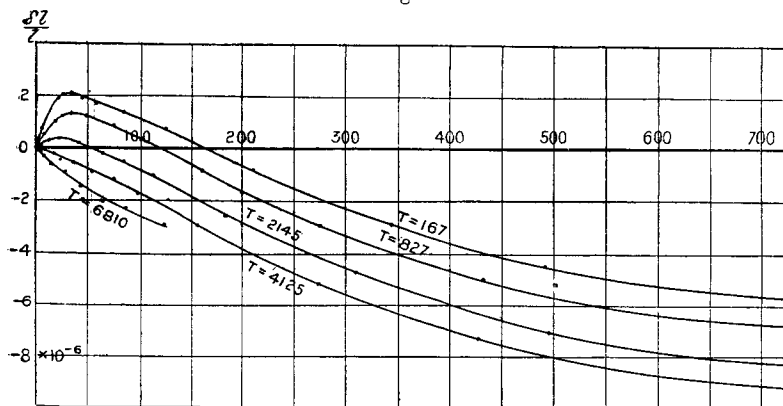
The wires tested had the following dimensions:—

Metals.....	Soft iron.	Wolfram steel.	Nickel.	Nickel-steel (45 p. c. Ni).	Nickel-steel. (35 p. c. Ni).
Length ...	20.74 cm.	20.97 cm.	20.70 cm.	20.75 cm.	20.73 cm.
Diameter...	0.139	0.060	0.136	0.150	0.144

4. *Soft Iron*.—Fig. 4 (p. 342) represents the curves of the change of length plotted against the magnetizing field; T is the tension per square millimetre. The specimen was very well annealed, and so the initial elongation was greatly reduced. From the figure we see that the effect of tension is to reduce the initial elongation. This reduction becomes greater as the tension increases, till the initial elongation vanishes at a tension of about 4 kilograms per square millimetre. When the tension exceeds this value the curvature of the curve is reversed. In fields greater than 40 c.g.s. units all the curves are nearly parallel to each other. The effect of tension on the change of length is comparatively larger when the load is small than when it is heavy.

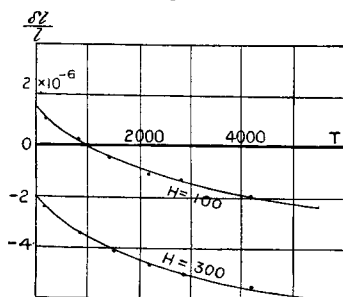
By making use of fig. 4 the curves showing the relation between the change of length and the tension under constant

Fig. 4.



field are obtained; some of them are given in fig. 5. We learn from these curves that the effect of loading on the magnetic change of length is not proportional to the load.

Fig. 5.

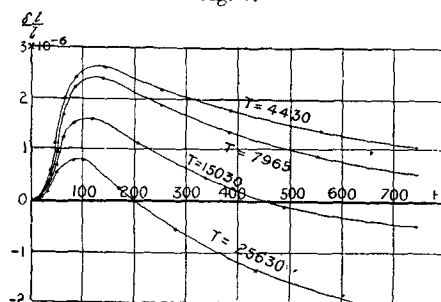


Generally speaking these results coincide with those of Bidwell. In our case the reduction of the initial elongation by tension is far greater than that with Bidwell's wire. The smallest tension at which the elongation vanishes is about four times greater in the latter case than in the former. The discrepancy perhaps arises from the fact that our specimen is comparatively soft as regards magnetization.

5. *Wolfram Steel*.—Fig. 6 represents the result for Wolfram steel hardened by stretching; the anomaly in the change of length for the steel was already pointed out by Prof. Nagaoka and one of us. This anomaly gradually disappears when the tension is increased, and at a tension of

25.63 kilograms per square millimetre the steel behaves like well annealed soft iron. The amount of the change due to

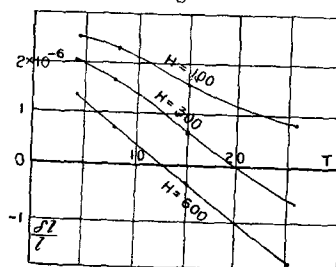
Fig. 6.



tension is decidedly small compared with other ferromagnetic metals.

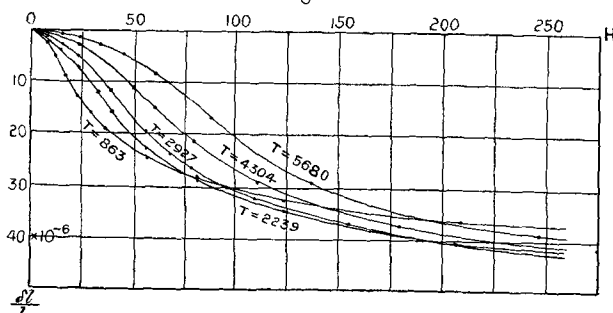
From fig. 7 we see that in Wolfram steel the effect of

Fig. 7.



tension on the magnetic elongation is nearly proportional to the tension.

Fig. 8.



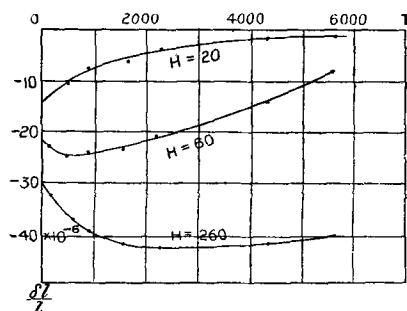
6. *Nickel.*—The results in nickel wire are graphically shown in fig. 8. In weak fields the effect of tension is to

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decrease the contraction of length, and the amount of diminution increases with tension. In strong fields the contrary is the case. The tension increases the magnetic change of length by an amount which increases with tension.

Each curve in fig. 9, showing the relation between the

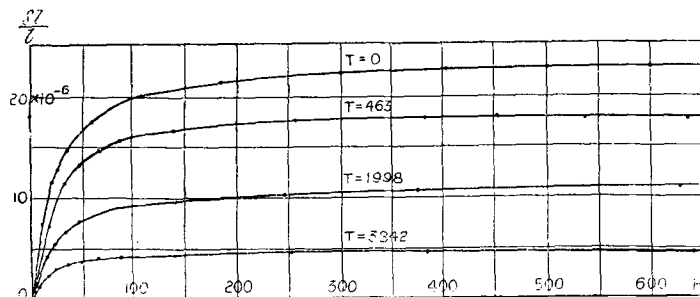
Fig. 9.



change of length and the tension under constant field, has a minimum point except in weak fields. This minimum occurs at a greater load as the field is increased. These results generally agree with those of Bidwell.

7. *Nickel-Steels*.—The change of length under constant tension of the annealed nickel-steel (45 per cent. Ni) is shown in fig. 10. The change of length under ordinary conditions

Fig. 10.

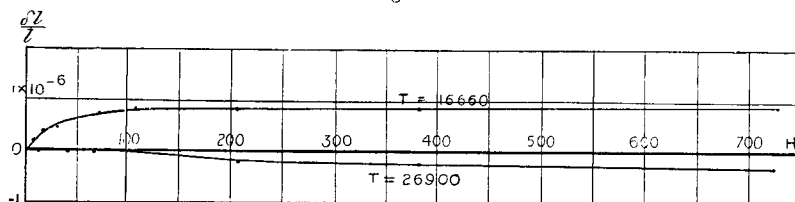


was already observed by Prof. Nagaoka and one of us. The maximum elongation, which is characteristic for iron, is not observed, but the wire simply elongates to an asymptotic value as the field is increased. Compared with other ferromagnetics the effect of tension is comparatively large. It diminishes elongation; by a tension of 1.4 kilograms per

square millimetre the elongation is already diminished by one half of its value corresponding to no tension.

To study the effect of heavy loading a wire of 0.50 mm. thick was made of the same alloy. After a moderate annealing it was subjected to an experiment to see whether it becomes shorter than the initial length when magnetized under a heavy loading. This actually occurred as given in fig. 11. With a tension of 26.9 kilograms per square milli-

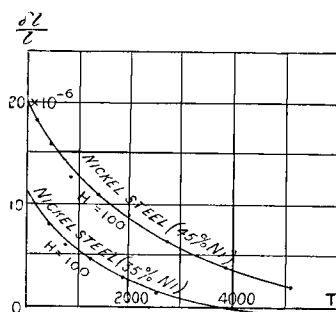
Fig. 11.



metre the length of the wire decidedly shortens when magnetized. Since the degree of annealing is different in the thick from the thin wire, the changes of length in these two wires for the same field and tension do not exactly coincide with each other.

The curve showing the relation between the change of length and the tension under constant field is shown in fig. 12; here we notice that the rate of the diminution of the change of length becomes less as the tension is increased.

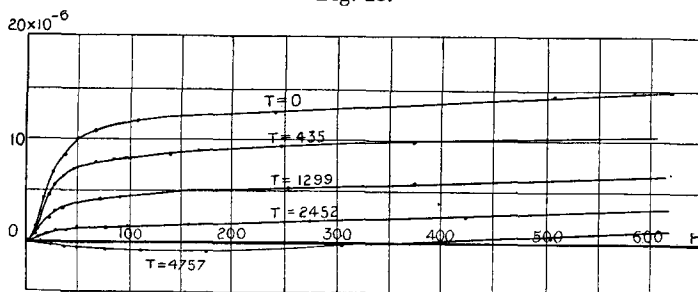
Fig. 12.



With another specimen of nickel-steel (35 per cent. Ni) the nature of the change of length and the effect of tension on it are generally the same as those of the former metal, as

shown in figs. 12 and 13. The course of the curves for large tension is, however, quite different from that for small

Fig. 13.



tension. For a tension of 4.76 kilograms per square millimetre the wire first contracts and then elongates when the field is increased. The curve of the change of length is therefore similar to that for cobalt. From fig. 12 we see that the rate of diminution decreases as the tension is increased.

In these two sorts of nickel-steels the curves for $T=0$ are the results of measurement obtained by Prof. Nagaoka and one of us, and reproduced here for the sake of comparison. It was at first our intention to perform the same experiment on a cobalt wire; but having at present no such material at our disposal, we leave the subject for future consideration.

In conclusion, we wish to express our best thanks to Prof. H. Nagaoka and also to Prof. A. Tanakadate for useful advice and kind guidance.

XXXVIII. *The Diffraction of Light from a Dense to a Rarer Medium, when the Angle of Incidence exceeds its Critical Value.* By EDWIN EDSER, A.R.C.S., Lecturer on Physics, Woolwich Polytechnic; and EDGAR SENIOR, Lecturer on Photography, Woolwich Polytechnic*.

THE well-known law of refraction

$$\sin i = \mu' \sin r,$$

indicates that, for a refracted ray to be formed, the angle of incidence, i , must be less than a certain critical value given by the equation

$$\sin i = \mu'.$$

* Communicated by the Authors.