Magnetic Qualities of Nickel (Supplementary Paper)

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XII. *Magnetic Qualities of Nickel* (*Supplementary Paper*).

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[Plate 17.]

The present paper is a supplement to one with the same title, by the author and Mr. G. C. Cowan, which was read before the Royal Society on May 17 (p. 325, *suprà*). In that paper experiments were described in which the effects of stress, consisting of longitudinal pull, on the magnetic permeability and retentiveness of nickel had been examined, and it was shown that longitudinal pull had an immense influence in reducing both induced and residual magnetism in nickel. It was, therefore, to be expected (as Sir William Thomson pointed out in his first discussion of the effects of stress on magnetic quality*) that longitudinal compression would make nickel more susceptible of magnetisation, and more ready to retain magnetic polarity. Experiments on the magnetisation of nickel under compression have now been carried out under the author's directions by two of his students, Mr. W. Low and Mr. D. Low, and the results are described below. Further experiments have also been made to investigate the magnetisation of nickel, in very strong magnetic fields, by the method already used for iron by the author and Mr. W. Low,† and the results of these are given at the end of this paper.

In dealing with the effects of tensile stress on magnetic quality, it is convenient to test the metal in the form of a long wire, long enough to prevent the ends from materially affecting the magnetic field throughout the main part of the length. But in dealing with stress of compression this method of approximating to the condition of endlessness is impracticable. Dr. Hopkinson has shown that a short bar may be brought to a condition of endlessness, suitable for the measurement of its magnetic susceptibility, by sinking its ends in a massive yoke of iron, which affords an easy path for the return of the lines of induction from end to end, outside the bar, and he has made use of this plan in determining the form of magnetisation curves for various samples of iron and steel.‡ This method lends itself well to experiments on the

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* 'Phil. Trans.,' 1878, or 'Reprint of Papers,' vol. 2, p. 358.

† "On the Magnetisation of Iron in Strong Fields" (1), 'Roy. Soc. Proc.,' vol. 42, p. 200; (2) 'Brit. Assoc. Report,' 1887, p. 586.

‡ Hopkinson, "Magnetisation of Iron," 'Phil. Trans.,' 1885, p. 455. In Dr. Hopkinson's experiments

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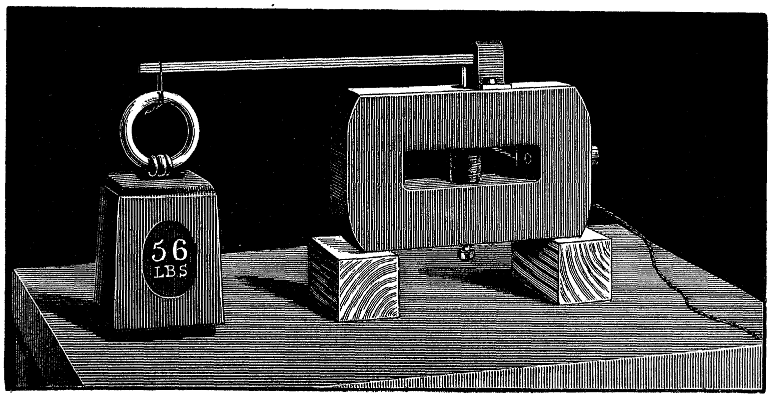
influence of compressive stress, for it is easy to fix the lower end of the bar in the yoke and apply weights directly, or by a lever, to the upper end. The arrangement adopted in the present experiments is shown in fig. 11.* The sample under test was a bar of nickel supplied by Messrs. **Johnson** and **Matthey** (which was found on analysis to contain 0·75 per cent. of iron). It was 10 cms. long, and was turned to a diameter of 0·656 cms. The yoke was of soft wrought iron, with a cross-section on either side of 67 square cms. The lower end of the bar was supported in the yoke by resting on the end of a screw-bolt; on the upper end a short plunger of wrought iron pressed, and through this the desired stress of compression was applied by means of a lever (fig. 11). The clear length of the sample, within the yoke, was 5 cms. Over this there was wound a magnetising solenoid of 250 turns, inside of which there was a small induction coil wound close to the metal. The magnetisation was determined by *reversing* the magnetising current while the induction coil was connected to a ballistic galvanometer. To find the residual magnetism the magnetising current was broken after reversal, and the effect of this break was subtracted from half the effect of the reversal. In every case several reversals were made before a measurement was taken; and the process of demagnetising by reversals† was resorted to whenever it was necessary to get rid of residual effects of previous magnetisation.

Fig. 11.



Arrangement for testing magnetisation of nickel under compression.

In the first place, the nickel bar was examined in the rather hard rolled or drawn state in which it was supplied, by applying magnetising forces which were raised, step

the bar was cut at the middle of its length, to allow an induction coil to be slipped out. This must have had the effect of making his measurements of susceptibility and retentiveness somewhat lower than they would have been had the bar been continuous. In the present experiments there was no joint in the bar itself, but there were, of course, joints between the ends of the bar and the yoke. These must have had some influence of the same kind, though less in amount, from the fact that the bar's ends were sunk a good way into the yoke, to give a large surface of contact.

[*] The figures are numbered consecutively with those in the former paper ('Phil. Trans.,' 1888, A., p. 325).

[†] 'Phil. Trans.,' 1885, p. 539.

by step, to about 150 c.g.s. units. Then the bar was demagnetised, a load was applied to the lever producing a stress of compression, and under this the bar was again magnetised. The process was repeated under one and another of a series of loads, the greatest of which produced a compressive stress of 20 kilos. per sq. mm.

The results of this group of experiments are shown in fig. 12, Plate 17, in the form of curves connecting $\mathfrak{I}$ (the intensity of magnetism) with $\mathfrak{H}$ (the magnetising force), for each of the following states of stress :—0, 1·9, 3·5, 6·8, 10, 13·3, and 19·8 kilogrammes per square millimetre. It will be noticed that the effect of compressive stress in augmenting the magnetic susceptibility of nickel is no less remarkable than the effect of tensile stress was shown (in the former paper) to be in reducing the susceptibility. The influence of stress is especially noticeable in the neighbourhood of the bend, or what WIEDEMANN calls the "Wendepunct" of the curves. This is well shown by the following Table, which gives the maximum value of the magnetic susceptibility κ for each state of stress :—

Intensity of stress of compression. Kilos. per sq. mm.	Maximum susceptibility. κ.
0	5·6
1·9	6·9
3·5	8·4
6·8	12·2
10	16·8
13·3	20·3
19·8	29

Concurrently with these observations another group was taken to determine the influence which the presence of these stresses of compression during magnetisation had on the amount of residual magnetism held by the metal when the magnetising current was broken at each stage in the process, the stress being maintained constant while the magnetising current was made and broken. Curves of the residual magnetism ($\mathfrak{I}_r$) in its relation to $\mathfrak{H}$ are given in fig. 13, for the same set of loads as the curves of induced magnetism in fig. 12 refer to. They show that a state of compression during the application and removal of magnetising force augments the residual magnetism even more than it augments the induced magnetism. In other words, the ratio of residual to induced magnetism is increased by the presence of compressive stress. It was found, in the former paper, that tensile stress reduced this ratio, so much, indeed, that under a strong pull there was scarcely any retentiveness left. Here, under compression, we have the opposite effect: there is enormous retentiveness when the stress is considerable. With no load the maximum value in the ratio of residual to induced magnetism is 0·56; with a compressive stress of 10 kilos. per sq. mm. it is 0·91; with one of 19·8 kilos. per sq. mm. it reaches the astonishing value of 0·96.

By way of showing more fully the influence of stress in facilitating the magnetisation of nickel we may draw, in ROWLAND's manner, curves connecting the permeability μ with the induction $\mathfrak{B}$. This is done in fig. 14 for three states of stress: (1) no load, (2) a compression of 10 kilos. per sq. mm., (3) a compression of 19·8 kilos. per sq. mm. In the first the maximum permeability is only 71, in the second it is 212, and in the third it is 357. The points directly found from the observed values of $\mathfrak{B}$ and $\mathfrak{H}$ are marked by dots upon these curves.

The nickel bar was then softened by heating it to redness in a charcoal fire, and allowing it to cool slowly; and experiments similar to the foregoing were made with it in the annealed state. The relation of induced and residual magnetism to magnetising force was examined while the annealed bar was in three states of stress: (1) under no load; (2) under a compressive stress of 3·5 kilos. per sq. mm.; (3) under a compressive stress of 6·8 kilos. per sq. mm. The stress was not increased beyond this for fear of hardening the bar by producing permanent set. Figs. 15 and 16 show the results of this group of tests. In fig. 15 the induced values of $\mathfrak{I}$ are shown by full lines and the residual values by broken lines, in relation to $\mathfrak{H}$. In fig. 16 the permeability μ is shown in relation to the induction $\mathfrak{B}$. It will be noticed by comparing figs. 15 and 16 with figs. 12 and 14 that the effect of annealing this bar is (as with the nickel wire used in former experiments) to increase the permeability at early stages of the magnetising process, but to reduce it at later stages, and to reduce the highest value to which the magnetism of the metal was raised. Fig. 16 shows that the curve of μ and $\mathfrak{B}$ for nickel suffers the same kind of inflection as the corresponding curve for iron* when the magnetisation is pushed to high values.

The ratio of residual to induced magnetism in this annealed nickel bar (as in all former samples both of iron and of nickel) passes a maximum in the neighbourhood of the "Wendepunct." The values of this maximum are 0·84, 0·88, and 0·91 for the three states of stress examined, namely, no load, 3·5 kilos. per sq. mm. and 6·8 kilos. per sq. mm. respectively.

A further experiment was made on the annealed bar to determine the initial value of the magnetic susceptibility under very feeble magnetising forces. For this purpose a new induction coil was wound on the bar, with many more turns than the former coil, and the early part of the curve of $\mathfrak{I}$ and $\mathfrak{H}$ was examined by the ballistic method as before. Fig. 17 shows the results for the two conditions of no load and a compressive stress of about 5 kilos. per sq. mm. With this, as with the nickel wire tested in earlier experiments, the curve of magnetisation is at first a sensibly straight line with a definite inclination. The initial value of the susceptibility is from 2 to 2·5, and the initial permeability is therefore 25 or 30. The initial permeability determined by this experiment has been utilised in plotting the point where the curve μ and $\mathfrak{B}$ in fig. 16 cuts the axis of μ.

It is interesting to notice that the residual magnetism after a very weak field has

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* 'Phil. Trans.,' 1885, p. 574; 'Roy. Soc. Proc.,' vol. 42, p. 208.

been applied is sensibly *nil.* It was only when the value of $\mathfrak{H}$ was raised to about 2 c.g.s. units that any trace of residual magnetism could be detected with certainty, although by that time the induced magnetism had become great enough to allow a tenth of it, or less, to have been determined without difficulty. As to the induced magnetism, it is to be noticed that the presence of stress has much less effect on the initial value of the permeability than it has when a later stage in the process of magnetisation is reached.

The experiments were completed by examining the magnetisation of nickel in very intense fields, by means of the "isthmus" method.* The same nickel bar was fitted with conical expanding end pieces of soft wrought iron, into which the ends of the bar were sunk, the whole forming a built-up bobbin with a short narrow neck of nickel, and the diameter of the neck was turned down to 0·399 cm. On the neck two induction coils were wound, one close to the metal and the other a little way out, so as to enclose an annular space, in which the field was measured by observing the difference in the inductive effects on the two coils. The bobbin was placed between the pole-pieces of the large electro-magnet of the Edinburgh University Laboratory, and its magnetism was measured by suddenly withdrawing it from between the poles, while the magnet was more or less strongly excited. Afterwards readings of the residual magnetism (which of course did not show itself when the bobbin was withdrawn from the field) were taken by removing one of the conical end pieces and slipping off the induction coil.

Measurements were made in fields ranging from 3450 c.g.s. to 13,000 c.g.s. Allowing for residual magnetism these produced values of the induction $\mathfrak{B}$, which ranged from 9850 to 19,800. Treating the magnetising field, which was measured outside the metal, as equal to the magnetising field within the metal itself (an assumption not far from true), we may calculate the permeability μ and the intensity of magnetisation $\mathfrak{I}$. The permeability ranged from 2·9 with a field of 3450 down to 1·5 with the highest field that was applied. The values of $\mathfrak{I}$ fluctuated irregularly between about 480 and 540, but showed no distinct progressive change either in the way of increase or decrease as the field was strengthened. The mean of $\mathfrak{I}$ in six determinations was 515, and this may be taken as fairly representing the limiting or saturation value of the intensity of magnetism for the particular specimen of annealed nickel dealt with. Saturation was practically reached at the lowest field, viz., 3450. Of the whole quantity, 515 for $\mathfrak{I}$, the residual part was 160, and this also was sensibly constant throughout the range of these experiments.

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* 'Roy. Soc. Proc.,' vol. 42, p. 200.

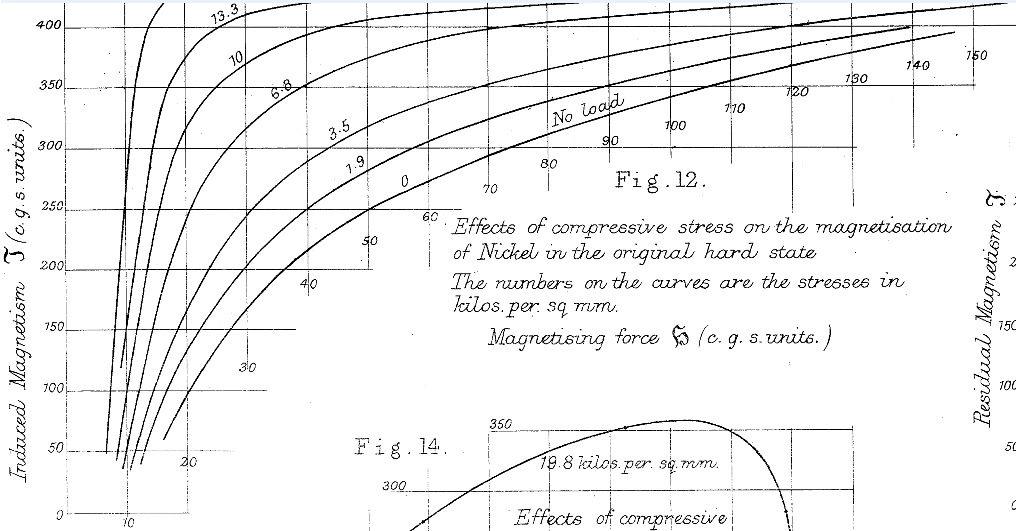
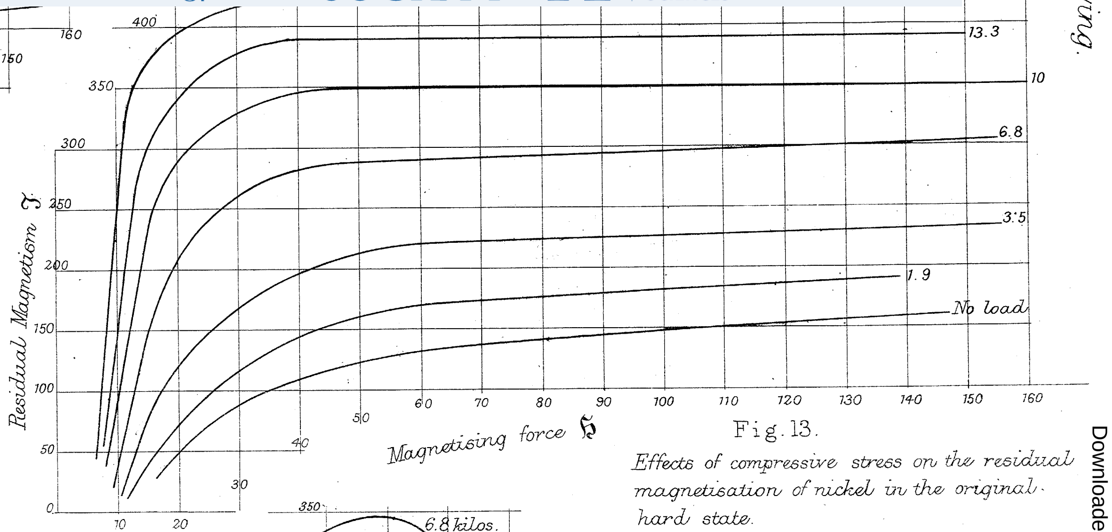


Fig. 12.

Effects of compressive stress on the magnetisation of Nickel in the original hard state

The numbers on the curves are the stresses in kilos. per. sq mm.

Magnetising force $\mathfrak{H}$ (c. g. s. units.)



Magnetising force $\mathfrak{H}$

Fig. 13.

Effects of compressive stress on the residual magnetisation of nickel in the original hard state.

The numbers on the curves are the stresses in kilos. per sq. mm.

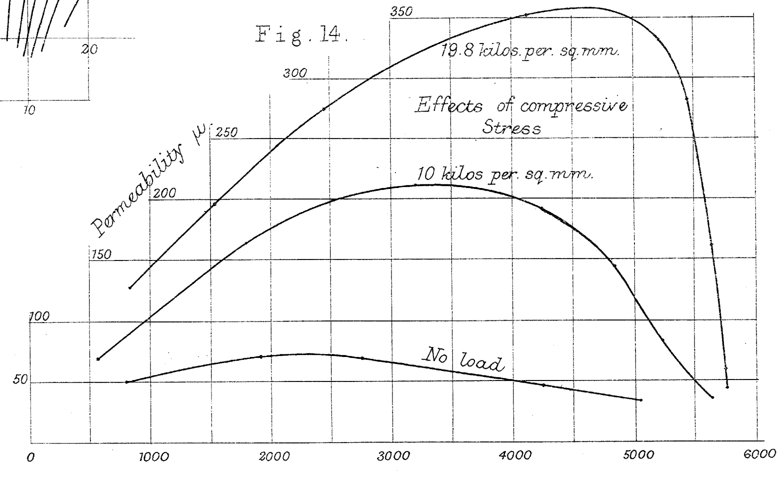


Fig. 14.

Permeability of Nickel in the original hard state

Magnetic Induction $\mathfrak{B}$

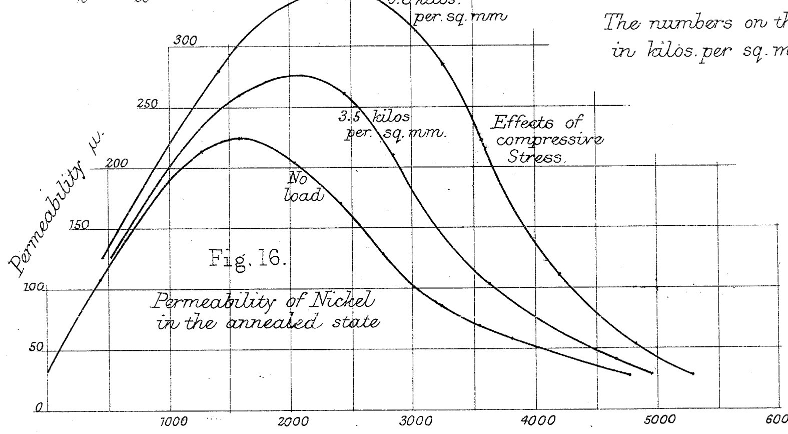


Fig. 16.

Permeability of Nickel in the annealed state

Magnetic Induction $\mathfrak{B}$

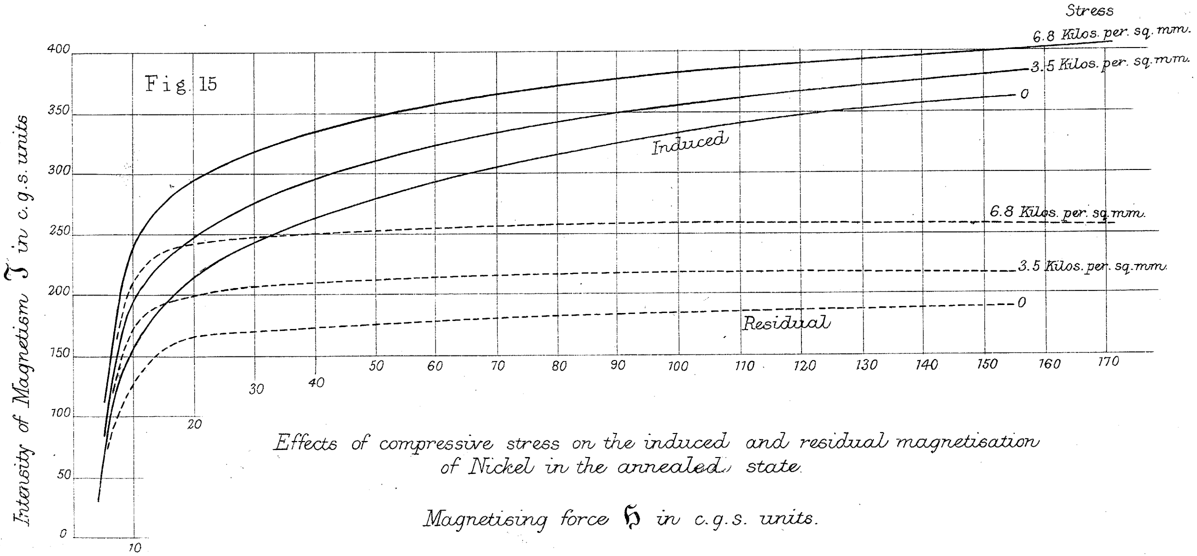


Fig. 15

Effects of compressive stress on the induced and residual magnetisation of Nickel in the annealed state.

Magnetising force $\mathfrak{H}$ in c.g.s. units.

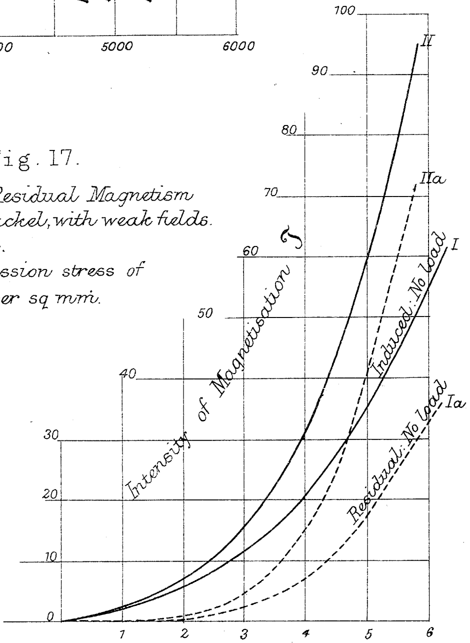


Fig. 17.

Induced and Residual Magnetism in Annealed Nickel, with weak fields.

I & Ia : no load.

II & IIa : compression stress of about 5 kilos. per sq mm.

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