CORRELATION OF THE MAGNETIC AND MECHANICAL PROPERTIES OF STEEL

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I. PURPOSE AND SCOPE OF PAPER

So much work on this subject has been done during the last few years that the prospects are very bright that a magnetic examination of steel will furnish information of practical value as to its fitness for mechanical uses, without at the same time injuring or destroying the specimen under test.

This paper is a review of the work done in correlating the magnetic and mechanical properties of steel. The International Association for Testing Materials has designated this as one of the important problems of to-day and has assigned its investigation to a special committee. A number of investigators are actively engaged on this problem.

Among the mechanical properties that have been studied in connection with the magnetic characteristics are hardness, toughness, elasticity, tensile strength, and resistance to repeated stresses. The well-known fact that not only do these various properties depend upon the chemical composition and the heat treatment, but that frequently very slight changes in the chemical composition or the heat treatment produce very appreciable effects on the magnetic and mechanical properties complicates the problem considerably.

The numerical data of this paper are taken substantially as they were presented by the original investigators. It is not to be assumed that the data are of great importance as absolute values of the various constants in question. In very few cases have pure materials been available for the investigators. Frequently the methods of measurement are open to objection and essential conditions of the experiment are not recorded. For example, the amount of manganese in a carbon steel may be undetermined and the heat treatment uncertain, although their influence is comparable in magnitude with that of carbon. However, as the purpose of this paper is to show that changes in conditions produce corresponding changes in both the magnetic and the mechanical properties, uncertainties in the absolute values will not vitiate their usefulness for this purpose.

There are at least three phases of this subject that warrant consideration. Of first importance is the comparison of the magnetic properties with the other physical properties of the material. If it can be shown that every variation in composition and method of preparation brings with it a corresponding variation in magnetic characteristics, and, further, that variations in magnetic conditions are always accompanied by other physical variations, then it is obvious that the general physical characteristics may be defined in terms of the magnetic constants. Whether such a procedure is feasible depends upon the fullness of our knowledge of the simultaneous magnetic and mechanical data and also upon the facility with which the necessary magnetic data are obtainable.

A second important phase of this subject is the variation in magnetic behavior as the test piece is subjected to the influence of stress. The correlation here is so close that the strains set up in a stressed bar are accompanied by simultaneous variations in the magnetic behavior which change in character as the magnitude of the strain with respect to the elastic limit changes.

Finally, mechanical inhomogeneities of whatever origin are mirrored by corresponding magnetic inhomogeneities. A magnetic test may therefore be of assistance in detecting flaws in material where the vital characteristic is reliability.

II. RELATION OF THE MAGNETIC TO THE OTHER CHARACTERISTICS OF STEEL

A number of experiments have been made which show a rather close connection between the magnetic characteristics and the chemical constitution. The following four curves are taken from the data of Gumlich:[1]

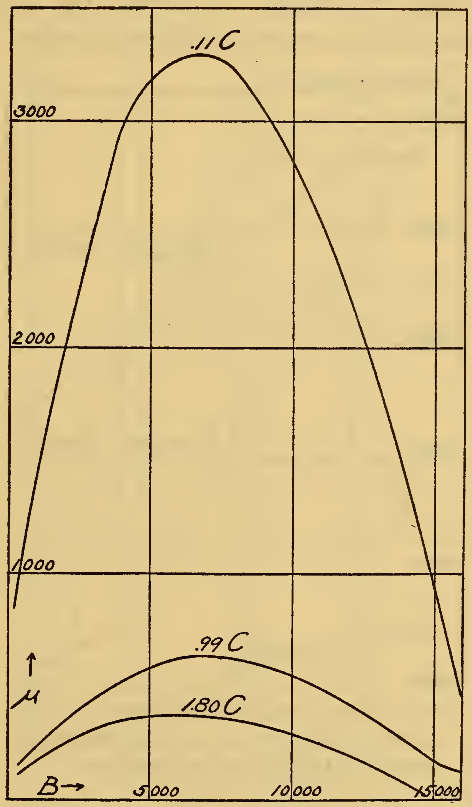

FIG. 1.—*Showing the variation of permeability with induction for steels of different carbon content*

Fig. 1 shows how the permeability varies throughout the course of the magnetization curve for different carbon content. This and other experimental work indicate that for a complete series of iron-carbon alloys, with no other differences than their carbon content, the carbon content is indicated by the permeability curve.

[1] Gumlich, "Magnetic properties of iron-carbon and iron-silicon alloys," Faraday Society Transactions, 8, pp. 98–114; 1912.

Fig. 2 shows the connection between the saturation values of magnetic induction (that is, the maximum values of $B-H$) and the carbon content. Pure iron has the highest saturation value for the series. An addition of carbon causes a decrease in the magnetization at a rate almost proportional to the amount of carbon added. This simple relation between the saturation value and the carbon content holds for any particular heat treatment. For different heat treatments, however, the saturation value changes with the carbon content at different rates. A comparison

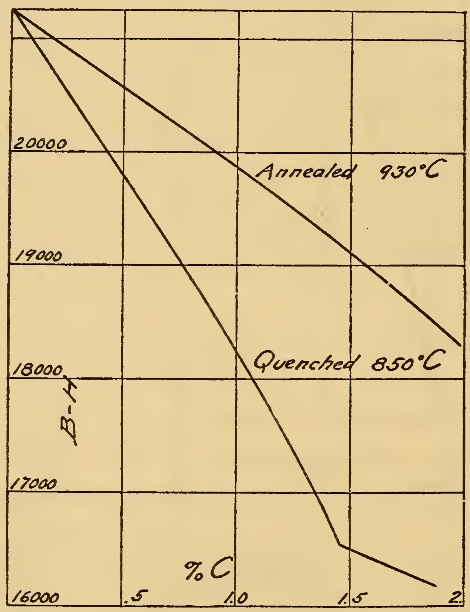

FIG. 2.—*Showing the magnetic saturation values of steels of different carbon contention the annealed and in the quenched conditions*

of the two curves shows that the reduction due to the presence of carbon is less for the annealed than for the quenched.

Fig. 3 shows the influence of carbon on the coercive force. Annealed steel has a coercive force which increases linearly with increase in carbon until an approximately eutectic alloy is reached.

For higher carbon contents the coercive force still increases linearly but at a decreased rate. Steel quenched at 800° C. shows a linear increase in coercive force for the hypoeutectic alloys and constant coercive force for the hypereutectics. Quenching at higher temperatures results in more complex relations.

Other elements than carbon will reduce the saturation value. Fig. 4 shows the rate of reduction of the saturation value for various additions of silicon. Here also the relation between the reduction in the saturation value and the percentage of alloyed element is nearly linear.

Waggoner[2] shows that magnetic hysteresis and the maximum strength of steels vary in the same way with changing carbon

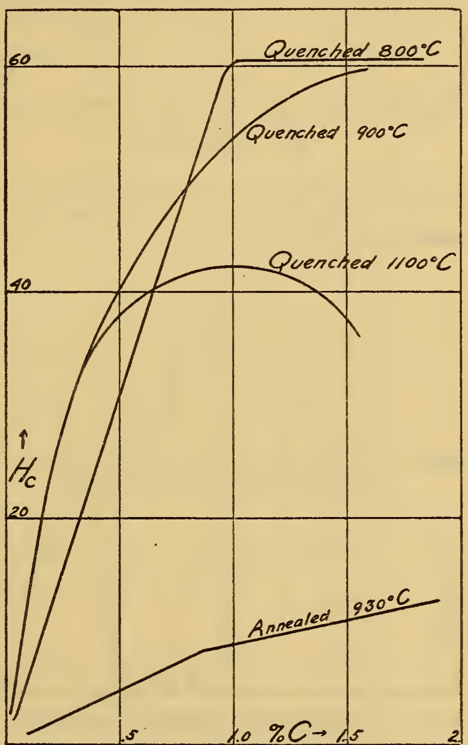

Fig. 3.—*Showing the variation of coercive force with carbon content for different heat treatments*

content. The characteristic curves of magnetic and elastic hysteresis show a marked similarity of shape. A comparison of the curve showing the relation of elongation under stress (or ductility) to the carbon content with the corresponding curve of magnetization and carbon content shows a striking similarity, indicating that the ductility of these alloys and their intensity of magnetization are affected in the same way by the chemical com-

[2] Waggoner, "A relation between the magnetic and the elastic properties of a series of unhardened iron-carbon alloys," Phys. Rev., 35, pp. 58–65; 1912.

position. The maximum susceptibility-carbon curve is also similar to the curve of ductility-carbon—that is, the maximum susceptibility decreases with increasing carbon until the eutectic is reached and then again increases with increase in carbon content.

Mars [3] shows that for a series of iron-carbon alloys there is a definite relation between the Brinell hardness and the residual induction as shown in Fig. 5.

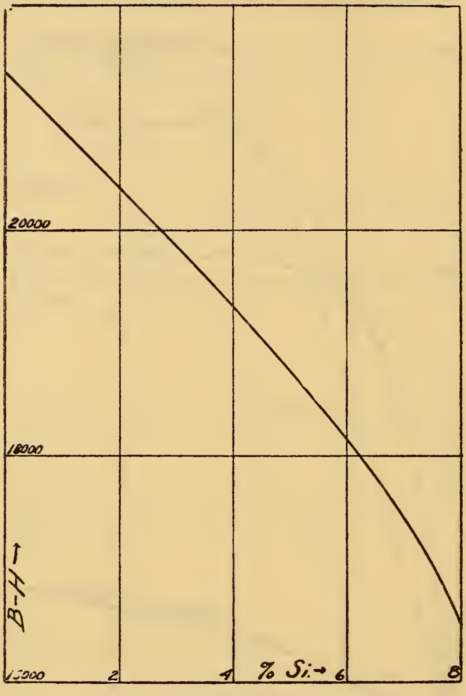

Fig. 4.—*Showing the variation of the magnetic saturation value with percentage of silicon in iron-silicon alloys*

Goerens [4] has shown the changes which the magnetic characteristics of a cold-worked steel undergo after various annealings. This steel was cold-drawn in five steps from an initial diameter of 7 mm to a final diameter of 2.7 mm. Fig. 6 shows the variation of the magnetic constants after annealing at various temperatures. Fig. 7 shows the corresponding mechanical characteristics. The mechanical properties are decidedly different for annealings below and above 500°. The same is true for the curve of maximum permeability. The curve of residual induction shows

[3] Mars, Stahl und Eisen, **29**, pp. 1673–1678; 1909. [4] Goerens, Stahl and Eisen, **34**, pp. 282–285; 1914.

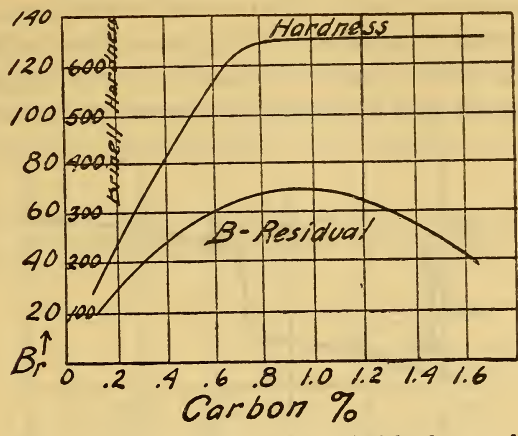

FIG. 5.—*Showing how the mechanical hardness and the residual induction vary with carbon content*

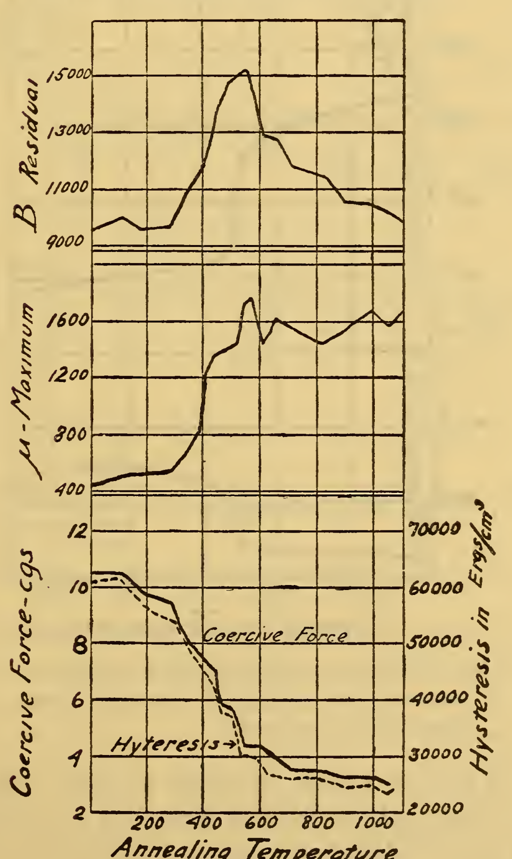

FIG. 6.—*Showing the effect of the annealing temperature on the magnetic properties of a mechanically hardened steel*

a sharp maximum at 500°. The curves for coercive force and hysteresis show steady decreases with increase of annealing temperature. In general, the magnetic characteristics respond to the annealing process in just as definite a manner as do the mechanical

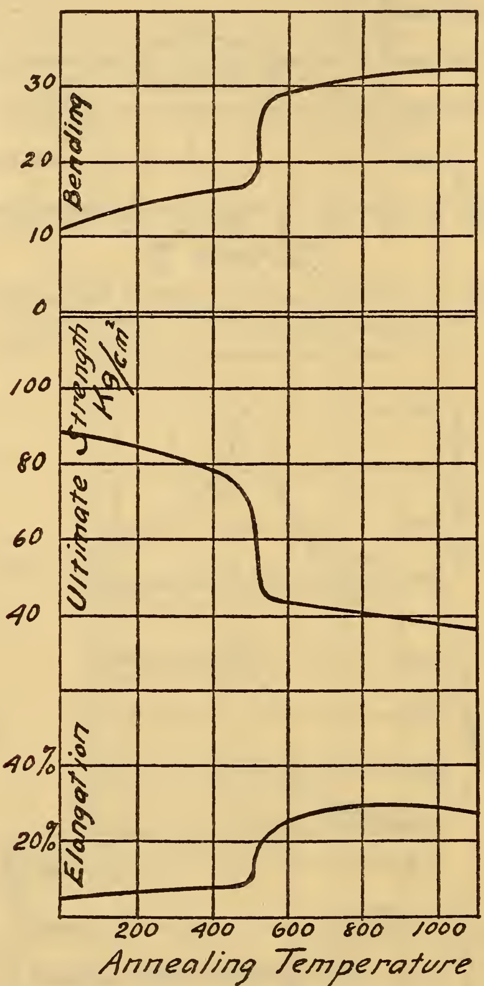

FIG. 7.—*Showing the effect of the annealing temperature on the mechanical properties of a mechanically hardened steel*

properties. In fact, it would be easier to deduce the heat treatment from the magnetic data than from the mechanical.

Fig. 8 may be considered as typical of the magnetic behavior of many alloy steels. The usual effect of quenching is to lower the induction curve. Subsequent drawing raises the curve again.

This improvement in the permeability increases with increase in drawing temperature up to a certain maximum when the curve occupies approximately the position of curve *C*. Higher drawing temperatures cause a reduction in the permeability and the curve approaches approximately the position of the annealed material.

Each curve corresponds to a given heat treatment and also to rather definite mechanical properties. The material of curve *B* is

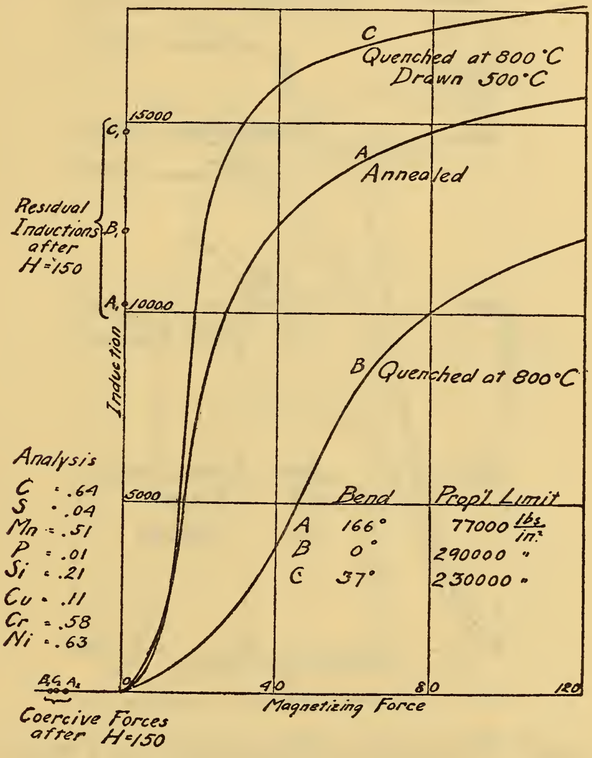

FIG. 8.—*Characteristic induction curves of an alloy steel*

so brittle that it is not usable, while that of curve *A* has a large angle of cold bend, but does not possess sufficient strength. The material of curve *C* has an ultimate strength several times that of curve *A*, accompanied by a fair degree of toughness. Not only do the normal induction curves show the characteristic effects of heat treatment, but also the residual inductions and the coercive forces after a magnetizing force of 150 gausses show such effects. It is possible to obtain a quenched and drawn steel whose induction curve approaches closely the position of the annealed curve.

However, two such steels would be at once differentiated by their differences in residual induction and coercive force.

Fig. 9 shows a set of characteristic curves for a spring steel of approximately 1 per cent carbon. Here, as in the case of the alloy steel, a high ultimate strength, coupled with a fair degree of toughness, is characteristic of those curves of Figs. 8 and 9 which are steep and of relatively high permeability.

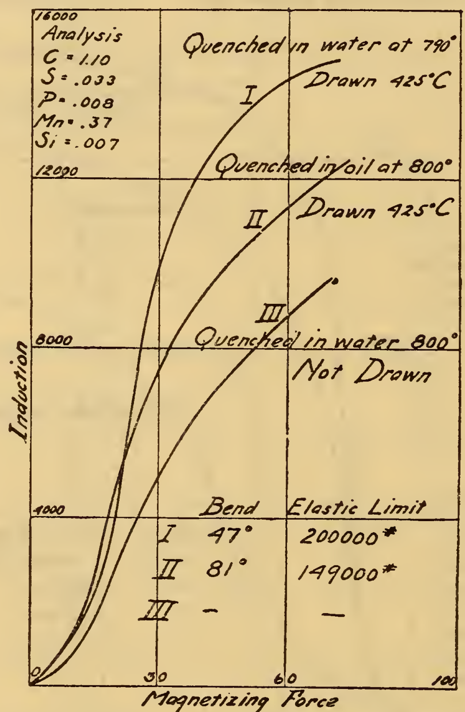

FIG. 9.—*Characteristic curves of a carbon steel*

Fig. 10 shows the magnetic characteristics of a low-carbon steel after various forms of heat and mechanical treatment. The similarity between the hardening effects of cold working and of quenching is shown by the similarity of the magnetic curves.

III. MAGNETIC BEHAVIOR OF STEEL UNDER THE INFLUENCE OF MECHANICAL STRESS

1. RÉSUMÉ OF EARLY WORK

Matteuci in 1847 noticed that the magnetization of a permanent magnet was increased when the bar was subjected to tension.

Villari showed in 1868 that the permeability of a bar of steel was altered when the specimen was subjected to tension. For low inductions this change is an increase in permeability, while for high inductions it is a decrease. The value of the induction at which tension does not alter the permeability is the "Villari reversal point." The permeability is modified by tension whether the tension is applied first and then the magnetizing force or vice versa. The effect is noticeable even after the tension has been applied and removed before the magnetizing force is applied. The effects of tension in these three cases differ in magnitude

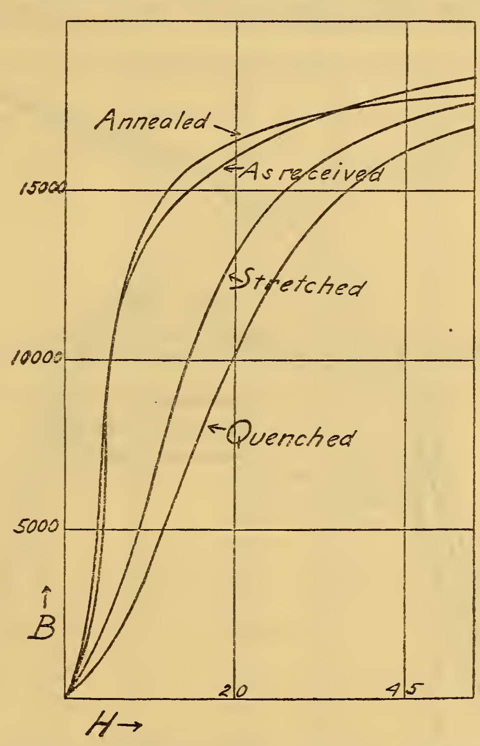

FIG. 10.—*Normal induction of a low carbon steel under different conditions*

rather than in nature. The effect is present whether a constant tension is applied while the magnetizing force is varied or a varying tension is applied to a specimen under a constant magnetizing force.

There is a certain value of the tension for which the induction is a maximum for a given field. The tension at which the induction is a maximum for a given field decreases with increase in field. In very strong fields this maximum may even disappear, so that the effect of any tension is to diminish the induction. On the other hand, in very weak fields the induction may increase with increase in tension for all stresses within the elastic limit.

All these effects are complicated by the phenomena of hysteresis and the initial changes are different from those that occur after the cycle of changes has been passed through several times.

J. J. Thomson, by a course of dynamical reasoning, has shown that there is a reciprocal relation between the changes in dimensions produced on magnetization and the changes in magnetization produced by mechanical strain. From this theoretical con-

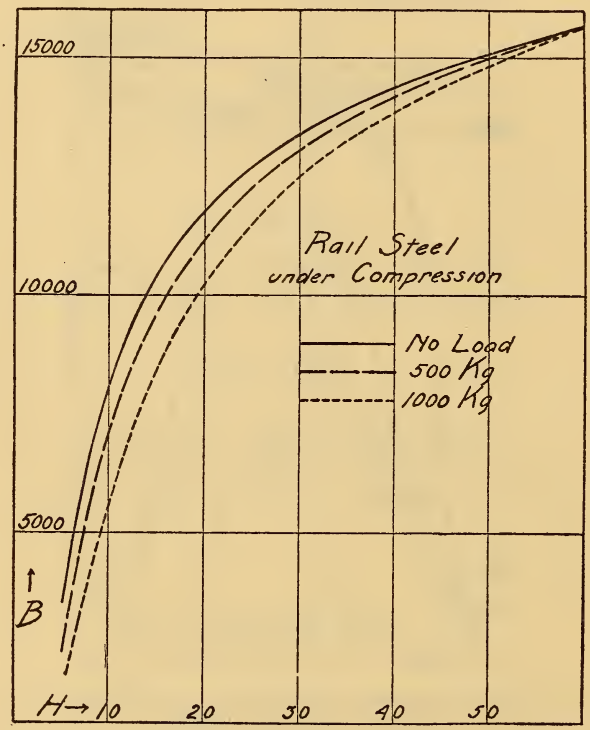

Fig. 11

sideration it is possible to foretell one set of phenomena from the data on the other. Both sets of phenomena have been carefully investigated and the reciprocal relation verified experimentally.

2. FOR STRESSES BELOW THE ELASTIC LIMIT

Figs. 11 to 16 are taken from an article by Smith and Sherman [5] and illustrate in detail the magnetic changes due to tension and compression.

[5] Smith and Sherman, Phys. Rev., N. S., 4, pp. 267–273; 1914.

In this investigation the materials studied were rail steel, mild steel, and silicon steel such as used in transformer plate. Test samples 60 cm long and 1 cm in diameter were subjected to various tensions and compressions and the magnetic induction curves simultaneously determined by the Burrows method.

If a low magnetizing force is applied to a rod under compression with a successively decreasing load, the permeability gradually increases with a steady decrease in this rate of increase as zero load is approached. If tension is applied, the permeability still

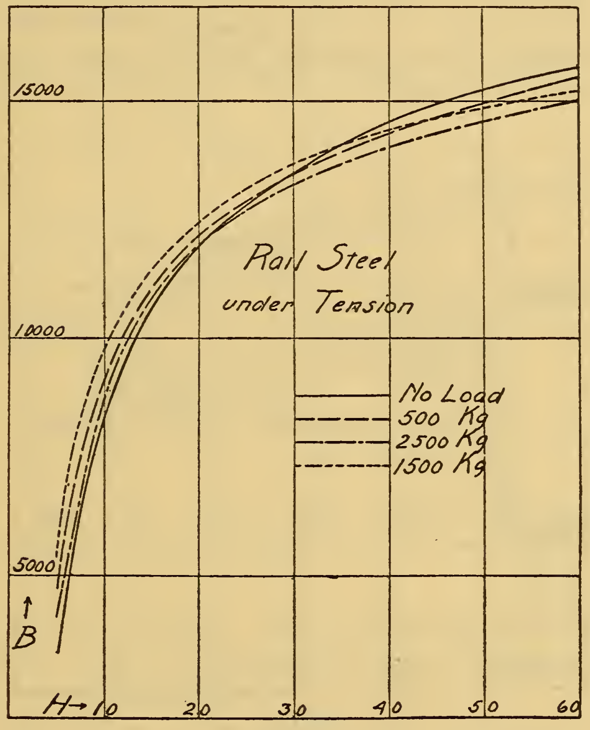

Fig. 12

increases at a diminishing rate until a certain value of load is reached at which the increase ceases. For larger loads the permeability becomes smaller as more tension is applied. The change in rate seems nearly constant and in the same direction throughout.

In all the samples the Villari reversal was found for tension, but not in all cases for compression, although the form of the curve indicated that at higher inductions the reversal might be expected for compression also. The effect of compression was to decrease the permeability at low values of *H* and to increase it at high values of *H*, but in much greater degree than the corresponding changes due to tension. The stresses ranged from a tension of 2500 kg per square centimeter to a compression of 1000 kg per square centimeter.

Magnetizing forces from 30 to 55 gausses were used. The greatest change in permeability was found in wrought iron, which showed at a magnetizing force of 15 a decrease from 14 200 gausses to 8600 gausses under a compression of 1000 kg per square centimeter.

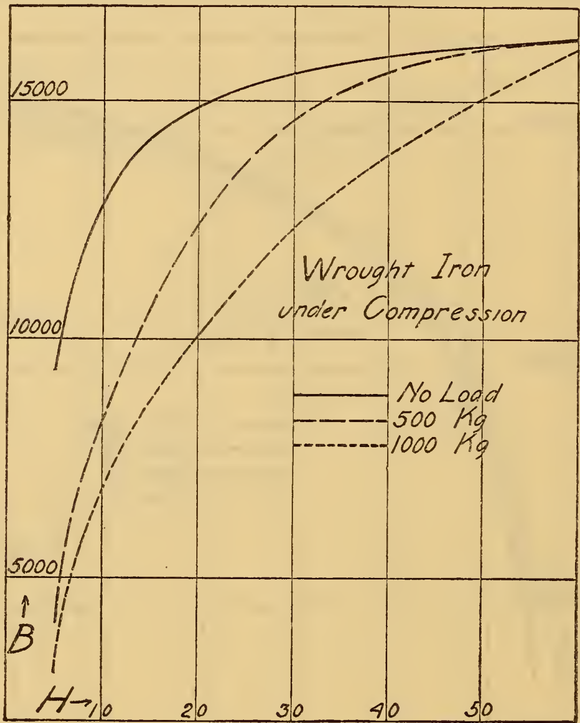

Fig. 13

The complicated manner in which the magnetic induction varies with the tension for different magnetizing forces is brought out in Figs. 17, 18, and 19.[6] Fig. 17 shows that for moderate values of the magnetizing force the induction is always increased by the application of a small tensile load and decreased by a large load. The intermediate load, which produces a maximum induction for the corresponding magnetizing force, is greatest for low magnetiz-

[6] Figs. 17–19, 22–25, and 27 are taken, with some modification, from the thesis of Paul D. Merica, "Ueber Beziehungen zwischen den mechanischen und den magnetischen Eigenschaften einigen Metalle bei elastischen und plastischen Formänderungen," Diss. Berlin; 1914.

ing forces and decreases as the magnetizing force increases, as shown in Fig. 18. The numerical value of the maximum increase produced by tension varies through wide limits, as shown by Fig. 19.

Fig. 20[7] shows the hysteresis in the magnetic induction when the tension is varied in a cyclic manner. It also shows the difference between the variation of magnetic induction when the load is first applied and that which occurs in succeeding cycles.

Fig. 21 presents in a slightly different form this same magnetic hysteresis after a change in tension. The magnetic effect of any mechanical stress depends not only upon the existing stress but also upon the previous stresses which have been impressed upon the specimen. Work done by the author tends to show that this aftereffect of a given load is reduced, if not completely obliter-

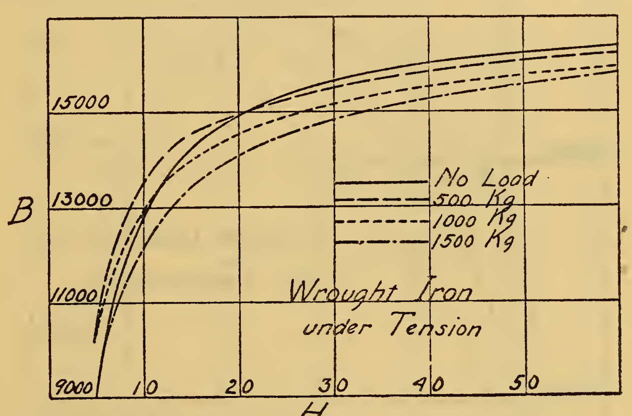

Fig. 14

ated, with the lapse of time. Merica shows that if the elastic limit has not been passed the magnetic effect of any stress may be wiped out by demagnetization.

In the experiment, the results of which are shown in Fig. 22, the test piece was strained beyond the elastic limit. At several stages the load was held constant while the bar was demagnetized and its induction determined. The hysteresis in both the magnetic and mechanical properties is worthy of note. For stresses within the elastic limit neither mechanical nor magnetic curve shows any hysteresis. We must not confuse the procedure of this experiment with that of Fig. 20, in which the magnetizing force was applied continuously without intermediate demagnetization.

[7] Figs. 20, 21, and 26 are taken, with some modification, from Ewing, "Magnetic induction in iron and other metals."

3. FOR STRESSES GREATER THAN THE ELASTIC LIMIT

The magnetic behavior of a bar under tension is altered by stressing beyond the elastic limit. The influence of stretching is shown in Fig. 23, where it is evident that both the contour and magnitudes of the curves are changed. Fig. 24 shows how the tension required to give the maximum induction for a given magnetizing force varies with the elastic limits which have resulted from previous stretching. The curve for the upper magnetizing force is so nearly a straight line that it is possible to determine intermediate elastic limits from the magnetic data.

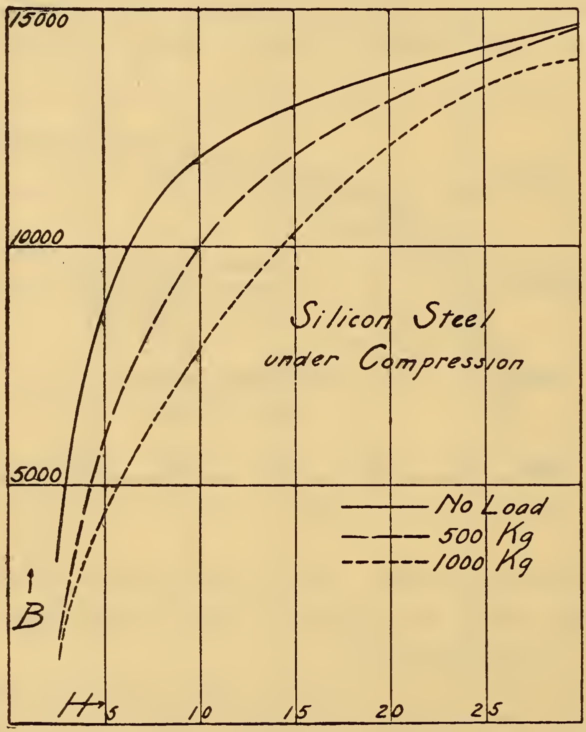

Fig. 15

Fig. 25 shows the manner in which the magnetic flux decreases during the elongation of the bar. The decrease in flux is not proportional to the elongation, so that it is evident that there is some change other than a decrease in cross section taking place within the bar. It is further evident that the greater part of this structural change takes place during the initial elongations.

The magnetic properties of all magnetic materials are modified under tension, though not all in the same manner. Nickel, for instance, shows an increased magnetic induction under compression and a decreased induction under tension, while iron shows the reverse. Fig. 26 gives some idea of the magnitude of these magnetic changes in nickel.

Fig. 27 shows the variation in induction with increase of tension for a sample of nickel steel. The change in induction as the tension reaches the elastic limit is very marked, both in the annealed and the stretched condition.

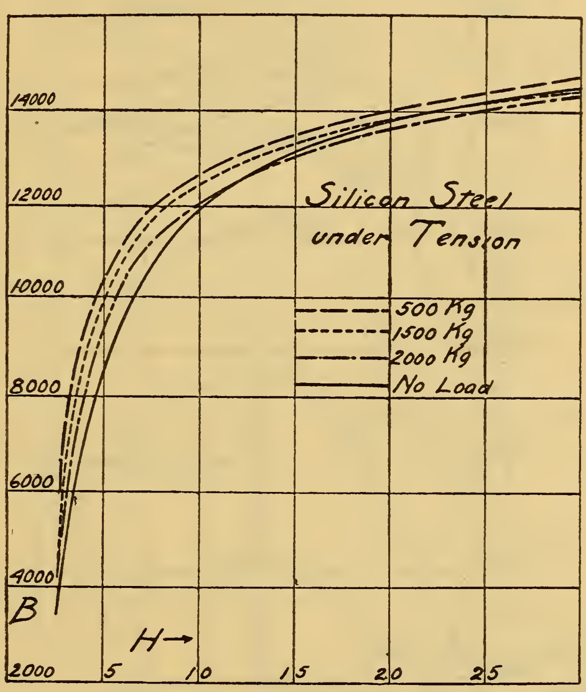

FIG. 16

A general view of the effect that tension below the elastic limit will have on a given material is obtained by a consideration of the curves of magnetostriction,[8] Fig. 28. If a material shows elongation for a given field, it also shows increased induction under tension, and vice versa, for the same field.

(*a*) **Experiments of Fraichet.**[9]—*Method.*—The bar under test is placed in a tensile testing machine and the jaws separated at a constant velocity. A solenoid which surrounds

[8] S. R. Williams, Phys. Rev., 34, p. 44; 1912.

[9] L. Fraichet, "Nouvelle méthode d' essai des métaux magnétiques," Ecl. Elc., 36, pp. 361–369 and 413–422; 1903.

the test bar carries the magnetizing current. A small test coil also surrounding the test specimen is connected to a suitable galvanometer. This test coil is linked with the flux in the bar under tension and any change in this flux gives rise to a corresponding emf which is indicated by the deflection of the galvanometer.

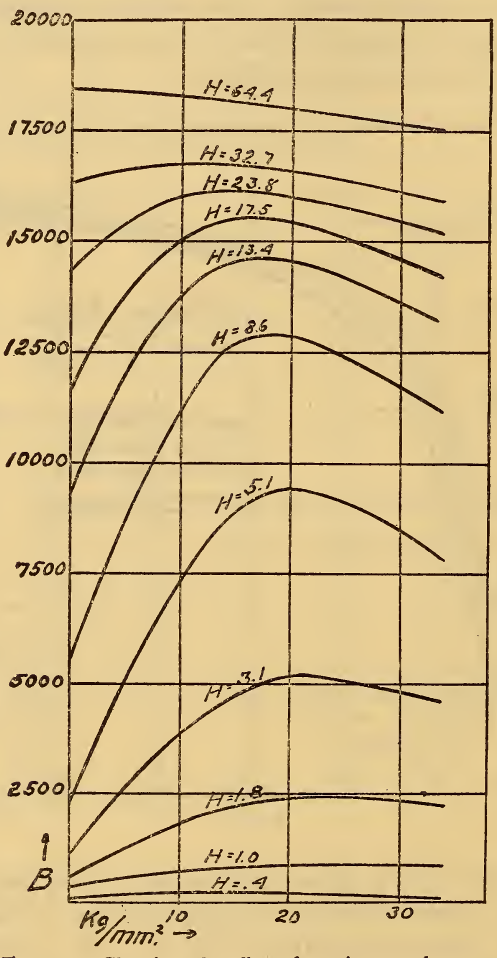

FIG. 17.—*Showing the effect of tension on the magnetization under different field strengths*

Causes of flux variation.—The flux may vary from any or all of three causes: (1) The reluctance of the joints and parts of the magnetic circuit other than the specimen may change; such variations occur when the tension is first applied but die out as soon as the grips of the machine make good contact with the specimen; (2) the reluctance will decrease as the continued ap-

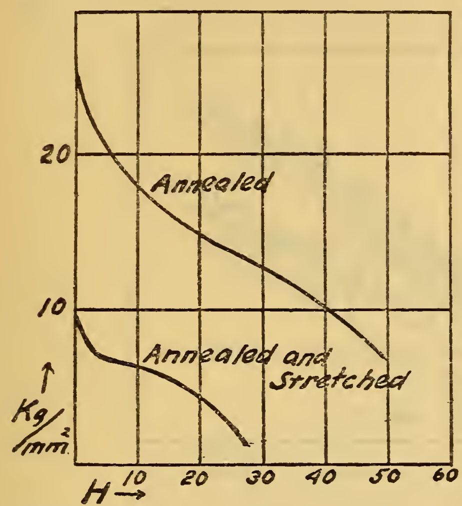

FIG. 18.—*Showing the tension required to produce the maximum induction for a given field*

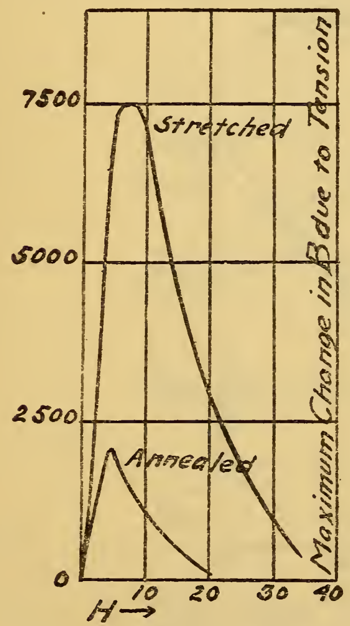

FIG. 19.—*Showing the maximum increase in induction which can be produced by tension*

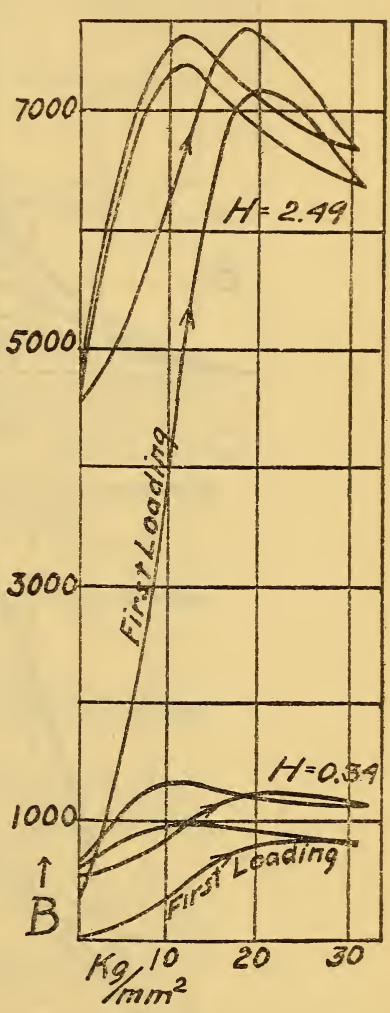

FIG. 20.—*Showing the changes in magnetic induction due to the loading and unloading of a bar under a constant magnetizing force*

plication of tension causes the bar to decrease in cross section; (3) changes in the molecular structure of the metal due to the cold working will probably cause changes in reluctance. Changes

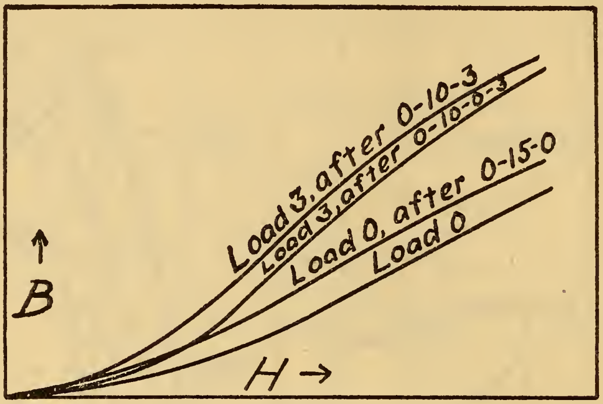

FIG. 21.—*Showing the effect on the magnetic induction due to loads which have been applied and removed before the magnetizing force is applied*

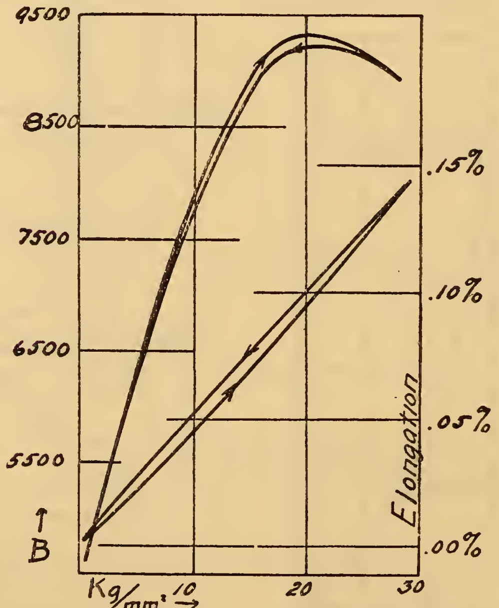

FIG. 22.—*Showing hysteresis in the magnetic and the mechanical properties of a steel under a changing tensile force whose maximum exceeds the elastic limit*

in the cross section will be manifested by gradual changes in reluctance, while changes in the structure will take place more or less suddenly.

In Fig. 29 the variation of magnetic flux is plotted against the time since the tension machine was started. Curve *II*, which may be taken as a typical curve of this type, shows several well-defined regions. The initial deflection of the galvanometer is positive and may be accounted for by improvement in joint contacts and the well-known increase in permeability due to

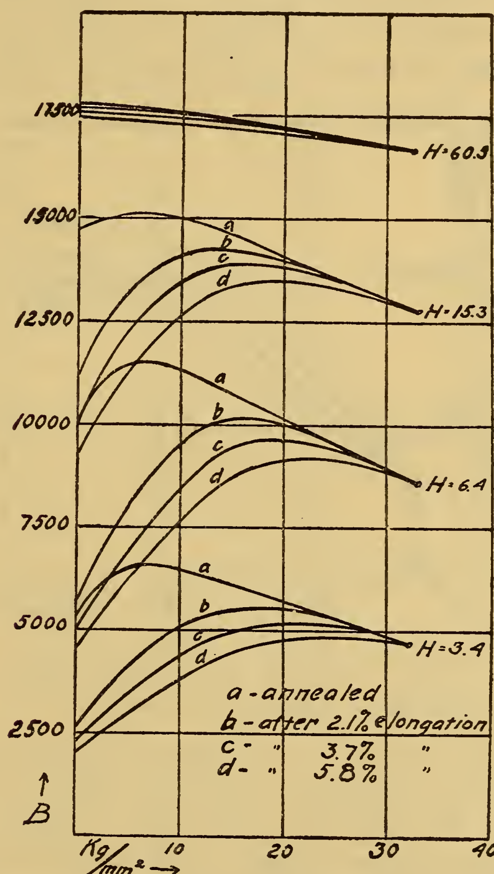

FIG. 23.—*Showing now the effect of tension on the magnetic properties is modified by cold working*

tension. This region is of no particular importance in the present series of experiments and may exhibit many apparent irregularities. The second region is one indicating a decreasing flux and ends with the point of maximum rate of decrease. This point corresponds to the limit of proportionality between stress and strain. This is the true elastic limit which we may define as the maximum load whose momentary application produces no marked modification in dimensions of the bar nor in physical or chemical properties of the metal

The third region is one of more or less violent vibrations of the galvanometer. These magnetic disturbances begin at the yield point of the metal, which is spoken of as the "apparent elastic limit." The fourth, or plastic region, is one of gradual decreasing galvanometer deflections terminated by a sudden but slight drop at the commencement of stricture. The last region shows a rapidly increasing reluctance, and terminates at rupture.

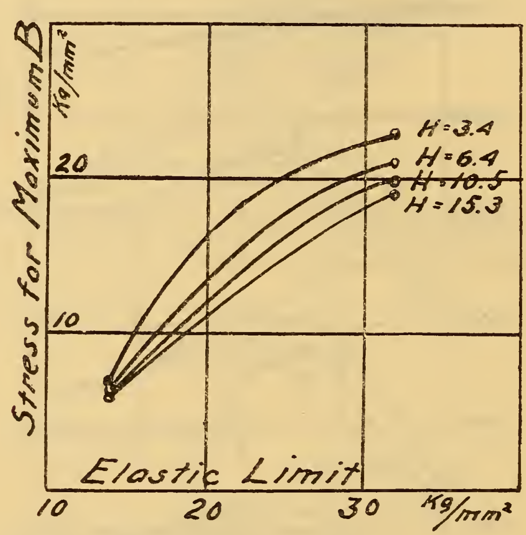

FIG. 24.—*Showing how the elastic limit of a series of cold-worked steels varies with the stress required to give maximum induction for a given field*

The other curves of Fig. 29 show that the nature of these main characteristics is not altered by the value of the magnetizing current employed. Fig. 30 shows the change in tension with time.

If in the initial bar the hardness of the volume elements varies continuously from one part of the bar to another, the molecular transformation of the same elements takes place in a continuous manner. This is what we observe in a quenched bar. The structure of the metal varies continuously. The galvanometer deflection at first increases, passes through a maximum corresponding to the true elastic limit, and finally decreases with a regularity dependent upon the initial homogeneity.

If the distribution of hardness is discontinuous the molecular transformation of the bar will be equally discontinuous, as indicated by the variations in the galvanometer deflections after the limit of true elasticity is reached. We observe these phenomena in bars of soft iron or annealed steel. An annealed bar is therefore composed of elements of varying hardness. Cold working reduces the number of these groups, and consequently produces an elevation of the true elastic limit. Quenching gives the same hardness to all those elements situated on the same concentric layer. A quenched bar is therefore composed of layers having a hardness decreasing from the outside inward.

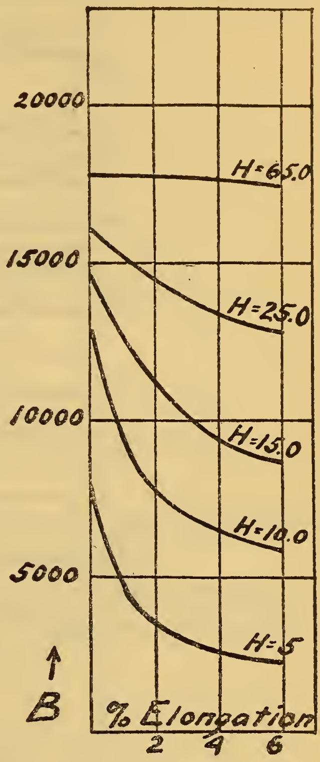

FIG. 25.—*Showing the decrease in magnetic induction corresponding to a given magnetizing force when the test specimen is stretched beyond the elastic limit*

When the hardest elements have been transformed by the cold working, the flux varies only as a result of change in dimensions. The elements glide one over the other. The specific load corresponding to the commencement of the plastic period is easily measured, and in the opinion of Fraichet may characterize completely the material.

Cold working acts on all the elements of volume and renders the bar homogeneous, and consequently the true elastic limit approaches the plastic load, which, in turn, approaches the ultimate. The effect of cold working is shown in Fig. 31. On the first loading we pass the true elastic limit below 4800 and at 4800 the metal is

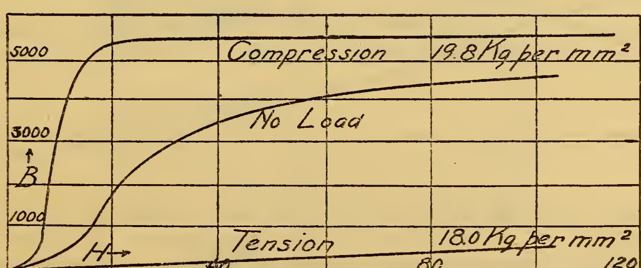

FIG. 26.—*Showing how the magnetization curve of nickel changes under tension and under compression*

yielding. When the load is removed and reapplied the true elastic limit is raised to 4800 and the yield point is about 4850. Re-

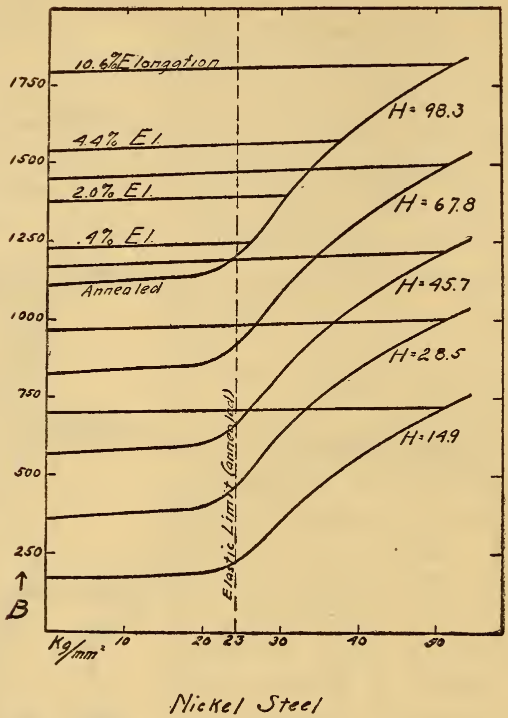

FIG. 27.—*Showing the variation of magnetic induction with tension for nickel steel*

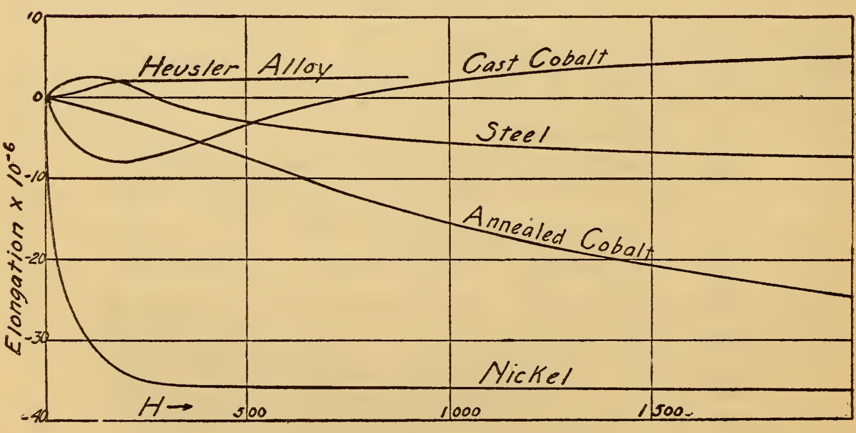

FIG. 28.—*Magnetostriction curves*

moving the load again and reapplying it results in a true elastic limit of 4850, followed immediately by the plastic yield and final rupture. In other words, the bar is homogeneous.

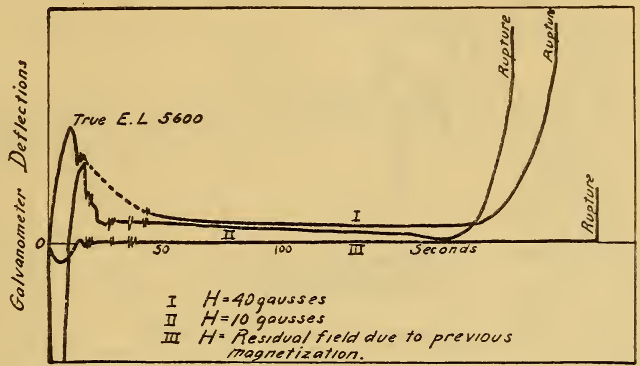

FIG. 29.—*Showing magnetic changes in a bar loaded to the point of rupture*

Fig. 32 shows characteristic magnetic curves for test bars of the same composition, but of different heat treatments.

The true elastic limit is easily determined by this magnetic method, and corresponds to a critical point of molecular equilib-

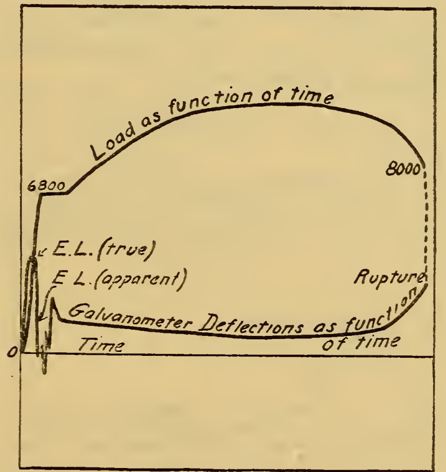

FIG. 30.—*Showing the changes in tension and in the magnetic properties when the tensile machine motor is driven uniformly*

rium. The apparent elastic limit or yield point is a function of the previous working of the metal, and consequently does not characterize the metal. The nature of the material is best indicated by the specific plastic load.

Fraichet[10], elsewhere in a paper on "Sudden variations in reluctance of a magnetized steel bar submitted to fracture as related to Lüder's lines," notes the appearance of lines on the

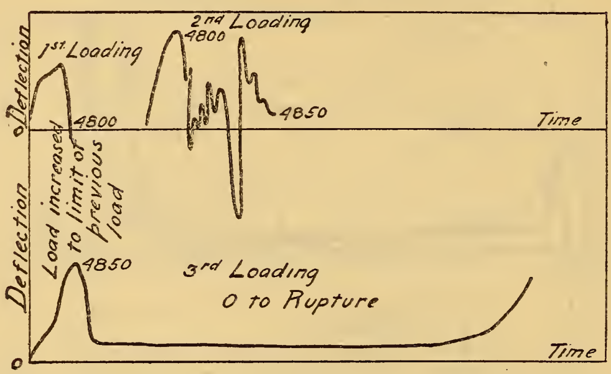

Fig. 31.—*Showing how the cold working of successive loadings beyond the elastic limit changes the magnetic and mechanical properties*

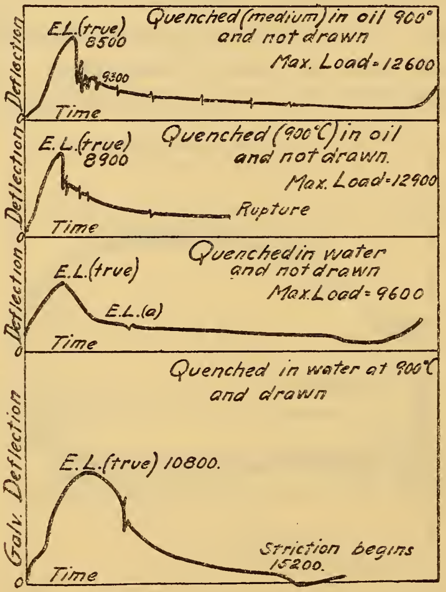

Fig. 32.—*Showing how the magnetic changes in a bar subjected to tension up to the point of rupture depend upon the previous heat treatment*

surface of a test bar of steel under a tensile force which correspond exactly with a sudden variation in the magnetic reluctance of the bar. It seems highly probable that the same cause gives

[10] Fraichet: C. R., 138, pp. 355–356; 1904.

rise to both these phenomena. Whenever the formation of fresh lines is observed the variation in reluctance is discontinuous, while no new lines are formed as long as the variation in reluctance is not abrupt.

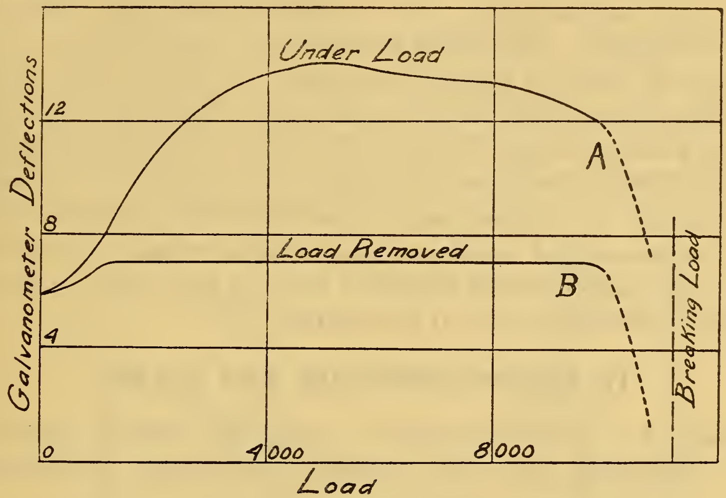

Fig. 33.—*Showing the magnetic induction under load and after the removal of load*

In Fig. 33 curve *A* shows the variations in magnetic induction of a bar of machinery steel under various loads in tension. The induction increases with initial load up to a maximum and then

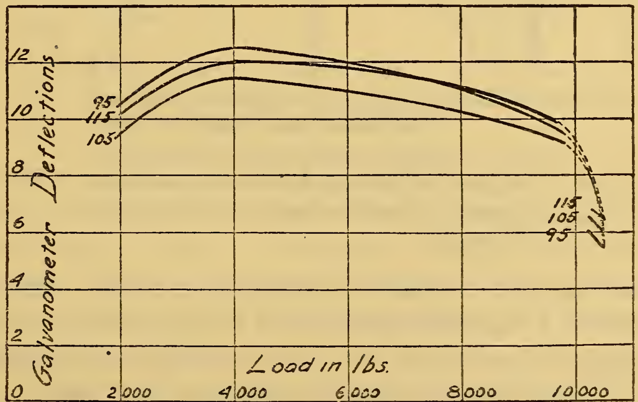

Fig. 34.—*Showing the variations in induction for different parts of a bar during tension*

decreases. At a load which corresponds roughly to the elastic limit the induction decreases abruptly. Curve *B* shows the inductions obtained after the loads indicated by the abscissæ have been applied and removed. This curve is almost a straight line throughout the greater part of its length and falls off abruptly as the elastic limit is reached.

Fig. 34 shows curves of induction under load in which the variation in the induction over three sections of the bar 10 cm apart were determined. The break occurred over the section 95, which, although it had the greatest induction for initial loads, showed the lowest induction at loads approximately the breaking strength. As the material began to yield, the load was decreased slightly, with a corresponding rise of induction as shown. If we assume that initially the greater part of the material at section 95 was under some internal tensile strain, we have at once the explanation of the higher initial induction and the lower final induction, together with the rupture at this section.

IV. INHOMOGENEITIES AND FLAWS

When a bar of steel is placed in a magnetic field the magnitude of the induction and other magnetic phenomena is determined

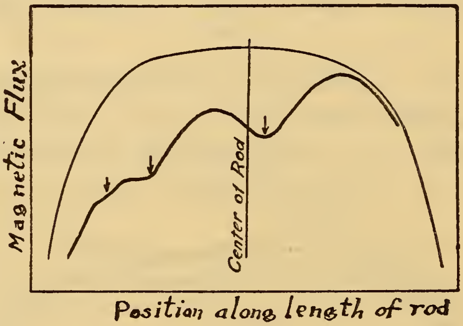

FIG. 35.—*Showing irregularities in distribution of flux in a rod which has been rendered nonhomogeneous by stamping numbers as indicated by the arrows*

by the nature and amount of material present. From this it follows that if a magnetic exploration is made along the length of a bar, magnetic variations may be expected in nonhomogeneous material. The following experiments bear this out.

In Fig. 35[11] is shown the variations in magnetic induction in a bar which forms one side of a rectangular magnetic circuit and is magnetized by a surrounding solenoid. The upper curve shows the normal variation of flux in a bar which is approximately uni-

[11] Burrows, Bull. Bureau of Standards, 6, p. 62, 1909 (Reprint No. 117).

form. The lower curve shows the variation of flux in the same bar after a single number has been stamped on the bar at each of the points indicated by the arrows. The magnetic changes produced by the stampings are evidenced by a decided reduction in the induction at these points.

Fig. 36[12] shows the variation in permeability along the lengths of each of two bars both before they have been distorted (dotted lines) and after they have been bent through a given angle and then restraightened (solid lines). After this last operation each bar was broken in a tensile testing machine. The permeability shows a remarkable change due to the bending. In the imme-

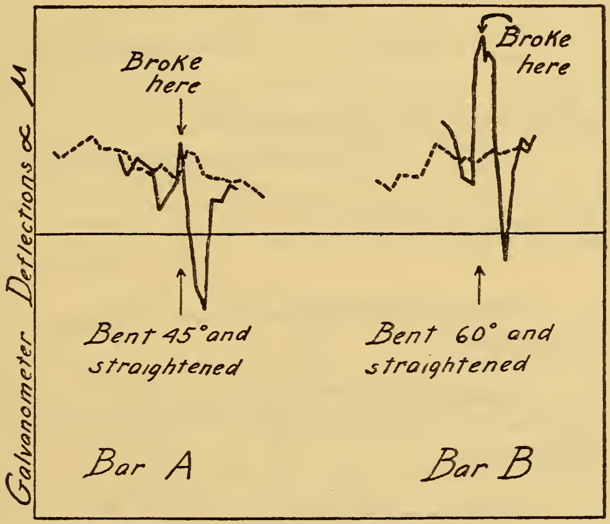

Fig. 36.—*Flux distribution of a bar before and after bending and restraightening*

diate neighborhood of the bend there is a region of increased permeability and close to it a region of decreased permeability. In each case the rod broke in the region of maximum permeability. In this connection we may refer back to Fig. 34, where, it was noted, the break occurred over the section which had initially a maximum permeability.

The magnetic homogeneity of a bar may be investigated in terms of the flux distribution when placed in a magnetic field. With a single stationary coil one may measure the total flux. With two opposing stationary coils the magnetic leakage may be

[12] Figs. 34 and 36 are taken from a paper by the author presented before the American Physical Society, April, 1912.

measured. With two opposing and movable test coils the variation in leakage may be measured. Mr. Sanford, of the magnetic section of the Bureau of Standards, has perfected the details of this last method of examination and the author is indebted to him for the following curves showing certain characteristic conditions.

In Fig. 37 are plotted the observations on seven bars which were originally homogeneous as shown by a preliminary examination

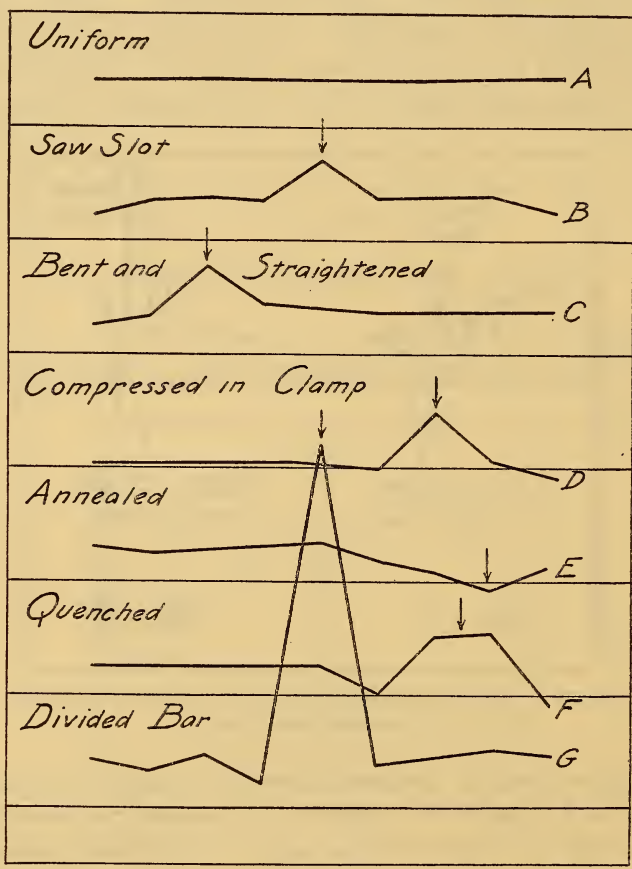

Fig. 37.—*Mechanical inhomogeneities as shown by variations in the rate of change of leakage*

and were later rendered inhomogeneous in the manner indicated. Curve *A* is the record of a uniform rod and is similar to the records of the other rods before modification. The criterion of a uniform rod is an approximately straight line. An upward projection indicates a magnetically hard spot and a downward projection indicates a soft spot. The sharp upward projection of *B* is due to a saw slot 3 mm deep in a rod of 12.7 mm diameter. Rod *C* was bent through an angle of 10° and straightened, while *D* was repeatedly compressed between the jaws of a small clamp operated by a thumb-screw. In each of the cases the magnetic inhomogeneity is similar to that caused by the saw slot. In *C* the bar was heated by a small flame and cooled in air. The resulting softness is apparent from the downward projection of the curve. *F* was heated over a greater length and quenched. The resultant hardness extends over a greater length, as might be expected. *G* is a bar which was cut in half and put together with a threaded joint and carefully finished surfaces, so that it presented the appearance of a continuous bar. The projection due to this treatment is striking.

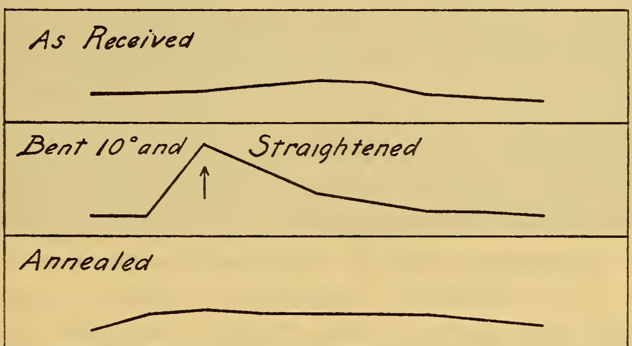

FIG. 38.—*Showing the effect of bending and restraightening and of annealing on the magnetic homogeneity along the length of a bar*

In Fig. 38 records are made of a bar as received, after bending and restraightening, and after annealing. It is to be noted that the cold bending produces a marked inhomogeneity which is entirely removed by subsequent annealing.

Such tests as these which indicate the presence of mechanical strains, coupled with the fact that such strains may be relieved by heating to a temperature below which structural changes occur, open up a wide field of possible applications.

1. INHOMOGENEITIES IN STEEL RAILS

At the present time the author is carrying on an investigation of the magnetic inhomogeneities along the length of steel rails.

The rail to be examined and a similar rail are placed side by side. The rail under test is surrounded by a narrow test coil which is in electrical connection with a galvanometer. Surrounding the rail for some distance on each side of the test coil are two magnetizing solenoids. Opposite these two solenoids and surrounding the auxiliary rail are two similar solenoids. The test coil and solenoids are rigidly connected together and mounted on a carriage which is free to travel along the test rail and its companion rail. Fig. 39 is a photograph of a pair of rails with the coils in place. Underneath the carriage is shown the electric motor which drives the apparatus along the length of the rails.

Any change in the magnetic induction in the test rails manifests itself by a deflection of the galvanometer coil. The position of the galvanometer coil is recorded by means of a spot of light reflected onto a photographic film. In order to make a continuous record the film is driven at a uniform rate by an electric motor. The galvanometer and recording apparatus are shown in Fig. 40. A great many modifications of the method of exploration were made. Some of the records, for example, were taken with one test coil surrounding each rail and coupled so that the emfs generated opposed each other.

To explore the length of a rail the current in the magnetizing solenoid is adjusted and the electric motors driving the carriage and the film started simultaneously.

In this preliminary work in order to get some idea of the importance of the magnetic irregularities observed several artificial defects were made in some ordinary 100-pound rails which happened to be available. These rails had all been in service and had been submitted to the bureau because of suspected imperfections. In general, they are from the same heat as other rails which have caused wrecks or otherwise failed in service.

In order to simulate the effect of a transverse fissure a saw slot 1 mm wide cutting away about 10 per cent of the section of the rail was made. This slot was filled in with high permeability transformer iron and the surface thus filled in was smoothed down with a file.

Fig. 41 shows the magnetic effect of the saw slot very clearly. In a later test of this same saw slot without the soft iron filling the galvanometer deflection was so violent that the spot of light went far beyond the bounds of the film. In either case the magnetic test shows the position of the slot within 1 cm. On another rail a similar slot was cut into the base and gave a record of similar characteristics.

To determine whether this method would detect a flaw in the web of a rail, records of the magnetic condition were made with holes drilled in the web. The effects of holes of various sizes are

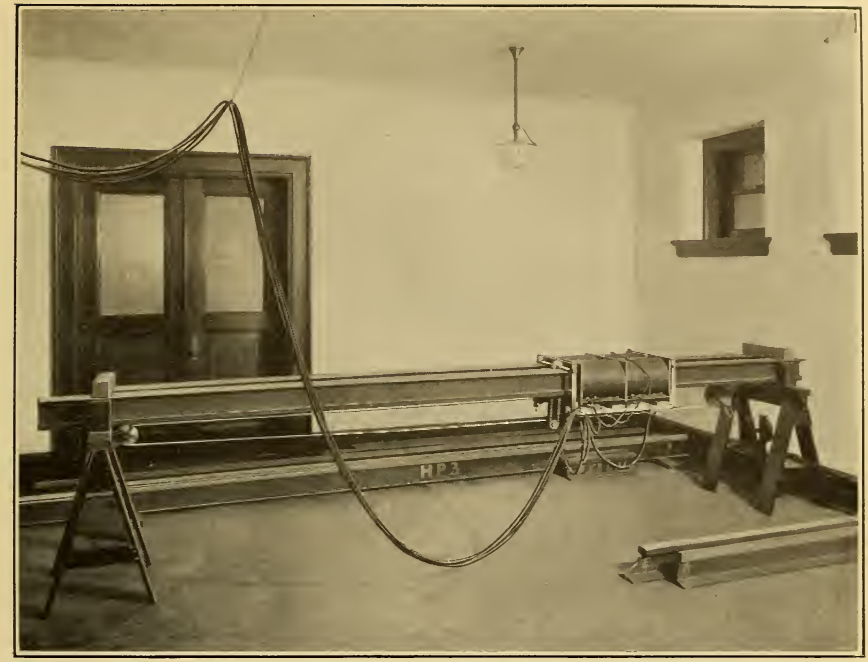

FIG. 39.—*Photograph of rail-exploring apparatus*

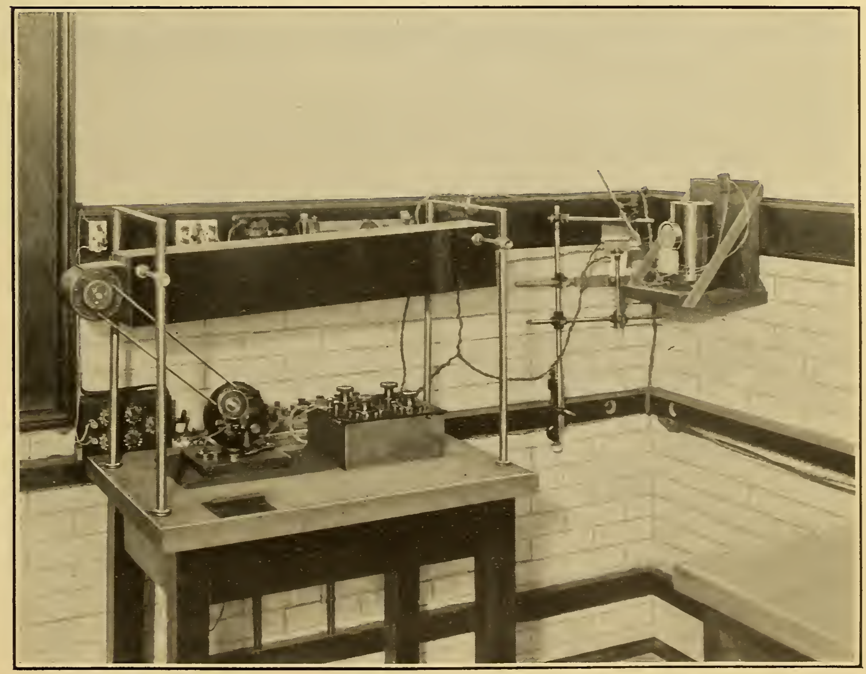

FIG. 40.—*Photograph of recording apparatus used in the exploration of rails*

shown in Fig. 41. It is quite evident that such a defect does make itself known by the magnetic exploration, and that the magnetic importance is proportional to the size of the hole.

In addition to the effects of the saw slot in the head and the holed drilled in the web, several other observations may be made on Fig. 40. The fact that the records are not all of the same length is due to slightly different rates of travel of the car in the

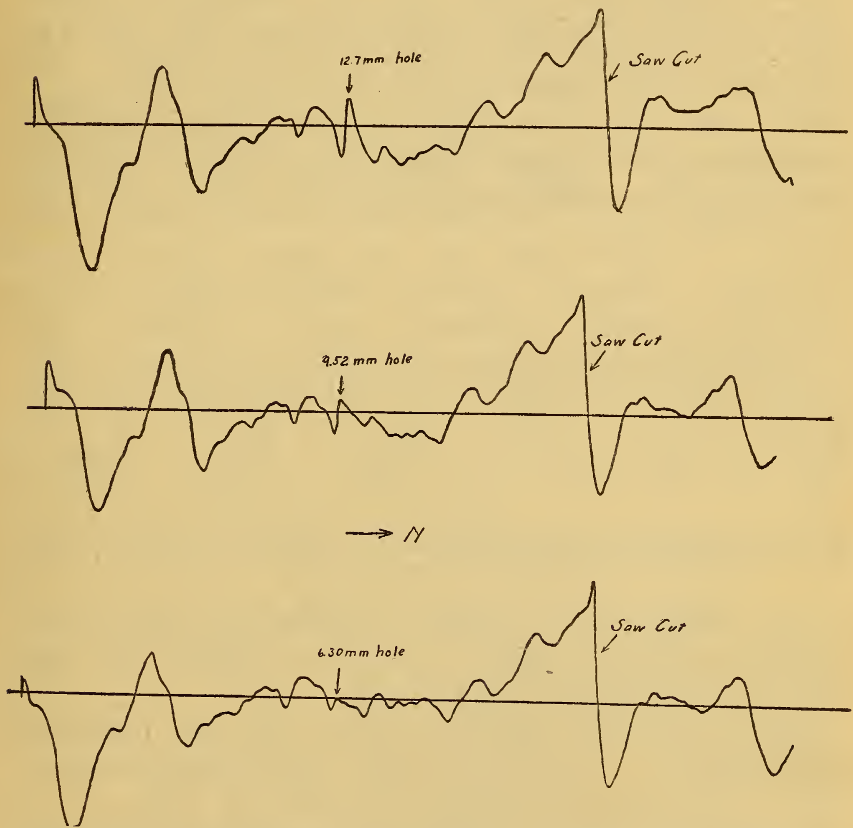

FIG. 41.—*Photographic record of inhomogeneities in a standard steel rail after service, showing the effect of artificial flaws*

various cases. The breaks in the curves are caused by shading the recording light beam at intervals corresponding to a carriage travel of 50 cm. The consistency with which the magnetic record repeats itself is quite evident from an examination. All the principal characteristics and most of the minor details of one curve are reproduced in the other two. The marked magnetic inhomogeneity noticed at the left of these records is due to some unknown characteristic of this region of the rail which, as yet, we have not had time to investigate.

In Fig. 42 of another rail the record shows a wavy form of remarkable uniformity. It appears from a comparison of the magnetic record with the tie marks on the rail that there is a cycle of magnetic variation which repeats itself at distances equal to the spaces between ties. The portion of the rail over the tie is magnetically harder than the intermediate portions. This is of considerable interest because of the fact that rail failures occur more frequently over the ties than in the interspaces. The irregularity in the middle of the curve is worthy of comment. At the point *A* the curve shows a relative hardening instead of the maximum of magnetic softness that might be expected. The rail head was carefully examined in this region and was found

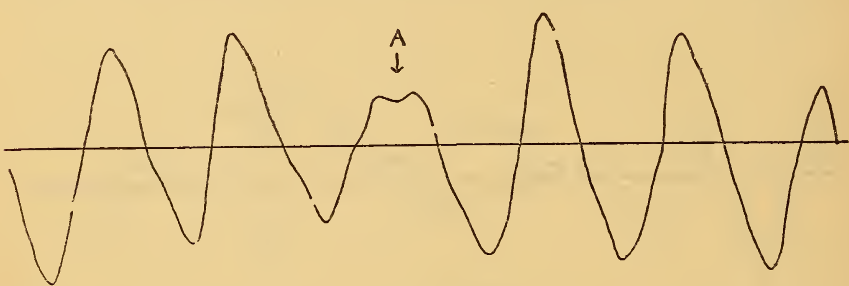

Fig. 42.—*Photographic record of a standard steel rail after service, showing the effect of tie strains and local hard spots*

to have imbedded in it a number of nodules of a metal of finer texture and greater hardness. It has been suggested that these may be small fragments from the rolls.

Quite an ingenious application of the fact that mechanical inhomogeneities are accompanied by corresponding magnetic variations was made by McCann and Colson[13] in 1908.

The apparatus consists essentially of a solenoid surrounding the mine hoist cable to be tested and connected in series with a suitable current source and measuring instrument. Any variation in the magnetic constants of the cable, due either to the breaking of individual strands or hardening caused by excessive strains, is indicated as soon as the defective portion passes through the apparatus. Suitable recording apparatus is provided so that a test of the entire cable is made every time the car travels the length of the shaft.

[13] Western Electrician, 43, pp. 76–77; 1908.

V. CONCLUSIONS

The experimental evidence, of which only a small portion has been presented in this paper, seems to point to the conclusion that there is one and only one set of mechanical characteristics corresponding to a given set of magnetic characteristics, and conversely there is one and only one set of magnetic characteristics corresponding to a given set of mechanical characteristics.

Although there is no evidence to refute the preceding rather broad statement, the utility of this generalization is decidedly limited by the complexity of the relations due to the large number of variables and the lack of sufficient quantitative data. Quantitative data, however, are gradually being obtained by the author and others who are working on this problem. The application of the magnetic tests is further limited by practical difficulties in testing irregular shapes. Even with these limitations, magnetic testing in conjunction with mechanical testing may be expected to be of considerable value in determining mechanical properties.

It has been shown that magnetic observations taken during the course of a tensile test indicate the time when the true elastic limit, the yield point, the necking down point, and the ultimate strength are reached. In addition, the magnetic data give some idea of the uniformity of the material.

If it is once determined what treatment is requisite for a given steel, a magnetic test may be used to determine whether or not the material has been brought into the desired condition.

It is quite possible that the magnetic data may be used to define a bar of steel. In no other manner than by a magnetic examination is it possible without doing violence to the specimens to determine whether two steel bars are identical in properties.

A determination of the magnetic uniformity of a piece of steel may be used as an index of the mechanical homogeneity.

A magnetic test indicates the character of the entire cross section of the metal, rather than merely a surface phenomenon, as in the case of certain hardness tests.

Notwithstanding the possibilities of the magnetic test, it must be remembered that at present they are possibilities only. Before the magnetic characteristics can be of much practical importance a great deal of investigation is necessary and a large number of accurate measurements on specimens of known chemical composition and heat treatment must be made.

Before a magnetic test can be of service as an indicator of the mechanical characteristics in any particular case, preliminary work must be done to determine the most suitable magnetic data and also the minimum amount which will give the desired information. Among the magnetic characteristics which may be used are permeability, residual induction, coercive force, hysteresis energy, etc., and each of these may be taken in connection with any one of a great number of magnetizing forces.

For a concrete case, suppose that the problem is to devise a magnetic test for a steel spring or a crank axle. The preliminary investigation would take some such course as the following:

1. Determination of magnetic normal induction curves and hysteresis data for test pieces made of the materials to be tested and submitted to the various heat and mechanical treatments that may be expected in practice.

2. Comparison of the above magnetic data with the corresponding mechanical data and the determination of the most suitable magnetic data to use.

3. Working out of the experimental details so that the required magnetic measurements may be made on the full-size commercial specimen.

4. Checking out of magnetic and mechanical data on the full-size specimens to be sure that the same conditions are fulfilled as in the case of the original test pieces.

Operations 1, 2, and 4 are time consuming, but do not offer any great difficulties that can not be overcome by patient intelligent experimentation. The third operation may offer practical difficulties due to irregularities in the shape of the material to be tested. Relatively long objects uniform in diameter, such as rails, steel rims, band screws, drills, and steel cables, present no difficulty. Relatively long objects whose cross section changes gradually from section to section, such as spring leaves, straight axles, and files, present comparatively little difficulty. Relatively long objects of irregular section, such as crank axles, present great but not insuperable difficulty. Short, thick castings present difficulties which for the present seem insuperable.

WASHINGTON, March 30, 1915.

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