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AN ALTERNATING-CURRENT MAGNETIC COMPARATOR, AND THE TESTING OF TOOL-RESISTING PRISON BARS

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ABSTRACT

This paper describes an instrument developed primarily for the purpose of testing tool-resisting prison bars, but which can be used for other practical applications of magnetic analysis. It is essentially an alternating-current bridge whose indications depend upon differences in the shapes of the magnetic hysteresis loops of the test specimen and a reference specimen of known quality. The instrument is simple to operate, portable, comparatively rugged, and operates from the ordinary alternating-current lighting circuit.

CONTENTS

I. INTRODUCTION

The purpose of this paper is to describe the alternating-current magnetic comparator developed during the course of an investigation on the nondestructive testing of tool-resisting prison bars and to discuss some of the results obtained with it. The investigation was undertaken at the request and with the support and cooperation of the Bureau of Prisons of the United States Department of Justice. The term "tool-resisting", for the present purpose, relates to material having such properties that it cannot be cut through with any tool or implement likely to come into the possession of a prison inmate. Obviously, it is very desirable to be able to inspect such bars in order to be sure that they have the requisite tool-resisting properties. It is also desirable that the testing method shall be reliable, convenient to apply, and nondestructive. The usual types of tool-resisting bars are of composite material consisting of two components, one hard and the other soft. The hard component is entirely surrounded by the soft material and, consequently, the ordinary tests for hardness cannot be applied.

Magnetic methods appeared to be the most feasible way of accomplishing the desired object and were given first consideration. A certain degree of success has been attained, and it seems likely that the remaining difficulties can be overcome.

II. PRELIMINARY EXPERIMENTS

There are several types of tool-resisting bars in use which differ with respect to the kind of steel employed and in the arrangement of the hard inserts. Two different arrangements of the inserts are illustrated in figure 1. This shows cross sections which have been etched so as to reveal the location of the inserts. The light-colored portions are the soft matrix material and the dark portions are the hard inserts. It is easy to see that the magnetic testing of such specimens presents some difficulties not ordinarily encountered in other applications of magnetic analysis. The principal difficulty is due to the small proportion of the material represented by the hard inserts whose properties are of primary importance. The main problem, therefore, was to discover some magnetic characteristic of the bars depending primarily on the condition of the hard inserts and whose variations are not masked by variations in the characteristics of the soft matrix material, which constitutes about three-quarters of the whole bar.

Before undertaking a systematic study of the magnetic characteristics of the bars, experiments were made with the apparatus shown in figure 2, which seemed to offer some promise. A short section of the bar to be tested was magnetized by means of a small U-shaped electromagnet. A magnetic balance was placed on the opposite side of the bar in a definite position with respect to the poles of the electromagnet. The balance consisted essentially of a short bar of magnetically soft material mounted on pivots in jewel bearings and mechanically balanced. By means of a spiral spring and a graduated dial, a measure of the force with which one end of the balance bar was attracted to the specimen could be obtained. A stop prevented the pivoted bar from making actual contact with the specimen. Readings were taken with the balance applied opposite each pole of the electromagnet and the results were averaged. In general, bars with hard inserts gave higher readings than those with soft inserts.

The apparatus was taken to the United States Industrial Reformatory at Chillicothe, Ohio, where tests were made on 152 bars. Two bars whose readings were 38.5 and 29, respectively, were removed from one window. The bar which gave the higher reading could not be cut through with a hand hacksaw, but the other was cut in two with little difficulty. The results on the other bars, however, were not very satisfactory. There was no definite separation into groups having high and low readings, respectively, and therefore the results could not be interpreted with any degree of certainty. Subsequent experiments in the laboratory led to the conclusion that variations in experimental conditions, not subject to control, influenced the results to such an extent that they could not be relied upon to indicate the quality of the bars. For this reason, no attempt at further development of the apparatus was made and attention was turned toward the discovery of some other method not subject to the same limitations.

Further experimental work was greatly facilitated by an experimental grille furnished by the Bureau of Prisons. This grille consisted of interchangeable bars of both kinds illustrated in figure 1. Some of the bars were hardened and some were soft. By the use of

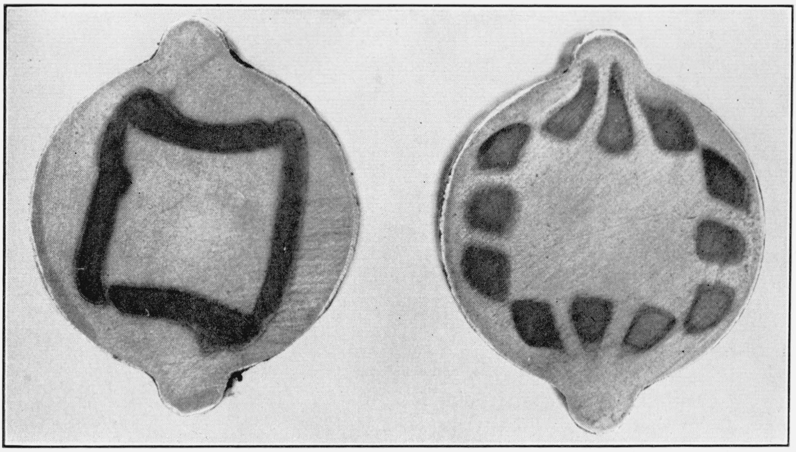

FIGURE 1.—*Typical sections of tool-resisting prison bars.*

The dark parts are the hardened inserts and the light part is the soft matrix material.

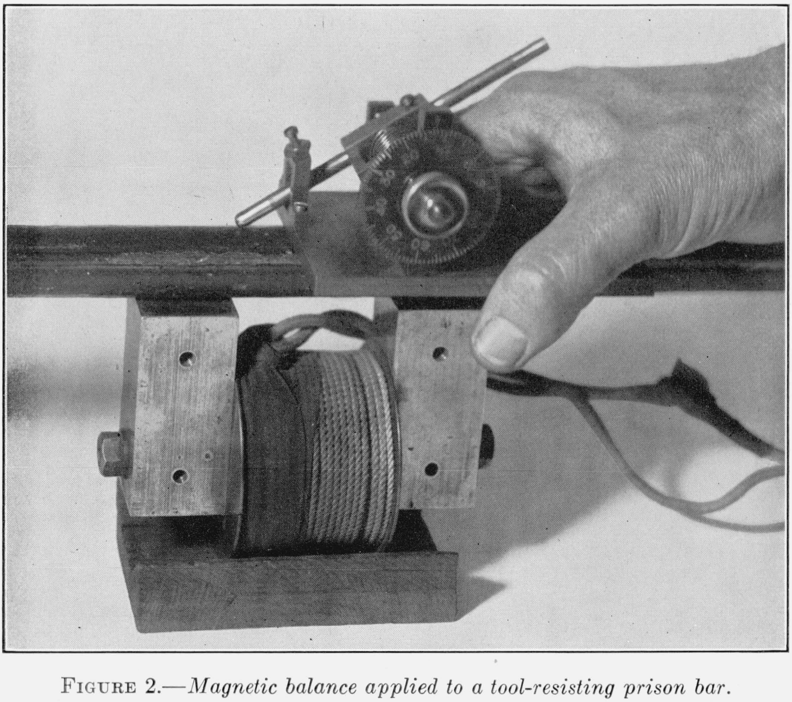

FIGURE 2.—*Magnetic balance applied to a tool-resisting prison bar.*

this grille, it was possible to set up in the laboratory various conditions likely to be encountered in the field.

Before attempting to devise new testing apparatus, the ordinary magnetic properties of several bars, both hard and soft, were determined by the usual methods. Figure 3 shows the normal induction curves for two bars. The lower curve was obtained for a bar so hard that it could not be cut with a hacksaw. The other bar had soft inserts and could easily be cut in two. Although these bars show a definite difference in permeability, small differences in the permeability of the soft matrix material, which constitutes three-quarters of the whole, could easily mask the effect of relatively large variations in the inserts.

Hysteresis loops for the same two bars are shown in figure 4. Although there is little difference in the values of residual induction

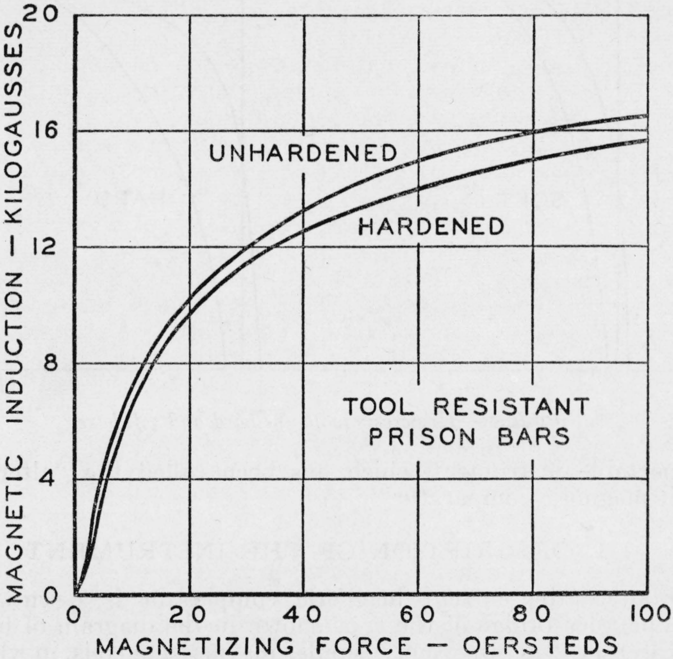

FIGURE 3.—*Normal induction curves for prison bars having hard and soft inserts.*

or coercive force, there is a marked difference in the shape of the two loops. The broadening of the upper part of the loop is characteristic of magnetically inhomogeneous materials and is due to the difference in the magnetic characteristics of the two kinds of steel of which the bars are composed. These results indicated that the shape of the hysteresis loop was the criterion most likely to be useful for distinguishing between hard and soft inserts.

As the determination of hysteresis loops by the usual direct-current methods is a rather tedious procedure, it seemed best to investigate the possibility of using an alternating-current method. Although most of the alternating-current tests which have been applied to other types of test specimen depend primarily on variations in permeability, several of these were tried out, but none of them proved to be satisfactory. A circuit was then tried out by which the distortion of the wave form of the magnetizing current due to hysteresis was shown by means of an oscillograph. By this method it was possible to distinguish between very hard bars and very soft ones, but it was not possible to detect smaller differences satisfactorily. However, a circuit was finally hit upon by means of which differences in distortion are indicated in numerical terms, and this circuit was incorporated

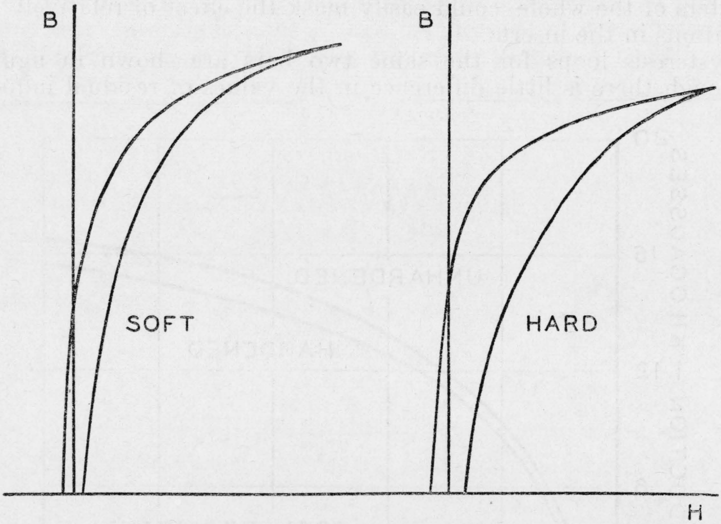

FIGURE 4.—*Hysteresis loops for hard and soft bars.*

in a portable instrument which has been called the "alternating-current magnetic comparator."

III. DESCRIPTION OF THE INSTRUMENT

The alternating-current magnetic comparator is essentially an a-c inductance bridge of the type shown in the diagram of figure 5. L_1 and L_2 represent two exactly similar magnetizing coils, in which are inserted a standard bar of known quality and the bar under test, respectively. The capacitors C_3 and C_4 are equal in value, and, in the present instance, each has a capacitance of approximately 20 microfarads. The detector circuit is connected between movable contacts on the slide wires R_1R_2 and R_3R_4. In the actual instrument, these slide wires are shunted by auxiliary resistors of sufficient current-carrying capacity not to overheat when the maximum current of 5 amperes is flowing. This also serves to make the setting of the contacts less critical. Current is controlled by means of a General Radio Variac connected to the ordinary a-c lighting circuit. The Variac is an autotransformer of special design and gives a very smooth control of the current, which is measured by a-c ammeter A. With no iron in coils L_1 and L_2, the bridge can be balanced so that no current flows in the detector circuit, and the following relation holds:

$$L_1-L_2=C(R_2R_4-R_1R_3),$$

where

$$L_1 \text{ and } L_2=\text{inductance, in henrys,}$$

and

$$C=C_3=C_4=\text{capacitance, in farads,}$$

and

$$R_1, R_2, R_3, \text{ and } R_4=\text{resistances, in ohms}$$

R_1 and R_2 include the resistances of L_1 and L_2, respectively.

If there is iron in the coils L_1 and L_2 the situation is more complicated. When a coil surrounding a core of iron is energized by a

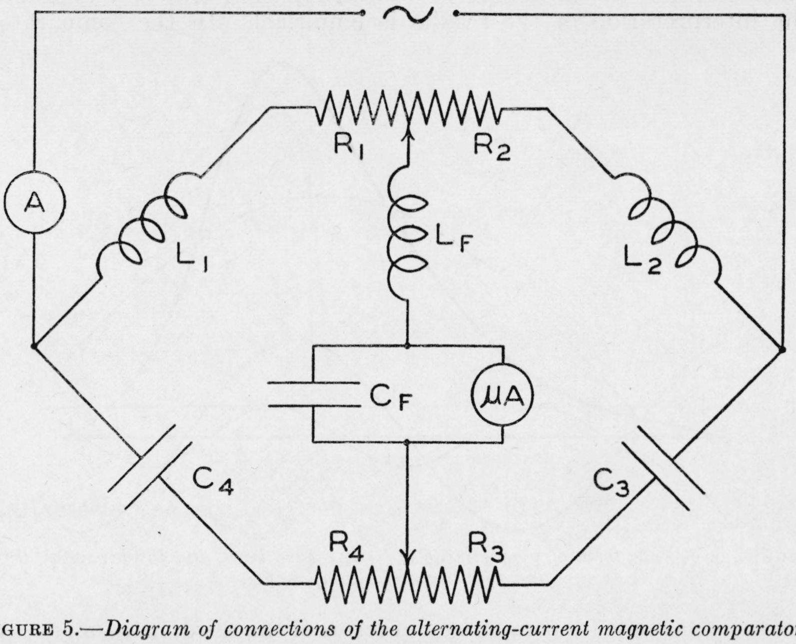

FIGURE 5.—*Diagram of connections of the alternating-current magnetic comparator.*

sinusoidal electromotive force, the flux also varies sinusoidally. The current wave, however, is distorted from the sine wave form on account of the magnetic hysteresis in the iron. The distorted current wave is made up of a combination of sine waves; a fundamental, having the frequency of the impressed voltage, and harmonics having frequencies which are odd multiples of the fundamental frequency. These harmonics differ in amplitude and phase. The amplitude is generally less the higher the harmonic, and harmonics above the seventh can generally be neglected. In figure 6, the magnetizing current corresponding to a sinusoidal variation of flux in the hard bar of figure 4 is shown, together with the fundamental, third, and fifth harmonics. If the magnetizing current is forced to have a sine wave form, the distortion is transferred to the flux wave.

The effect of the distortion due to hysteresis is to introduce in the arms L_1 and L_2 of the bridge electromotive forces having frequencies which are odd multiples of the fundamental frequency and which, in general, differ from each other in magnitude and phase. It is possible to obtain a complete balance only when the two specimens are exactly alike magnetically. When the specimens are not alike, the slide wire contacts are set to give the minimum value of current in the detector circuit and this is taken as the reading. By using a filter circuit in connection with the detector, comparison can be made in terms of differences in a given harmonic. These differences depend not only upon the respective magnitudes of the harmonics but also upon their phase relations. There is no provision in the present instrument for differentiating between differences in magnitude and differences in phase relation so the comparison is on a purely arbitrary basis and the interpretation of the results is empirical. In the comparator,

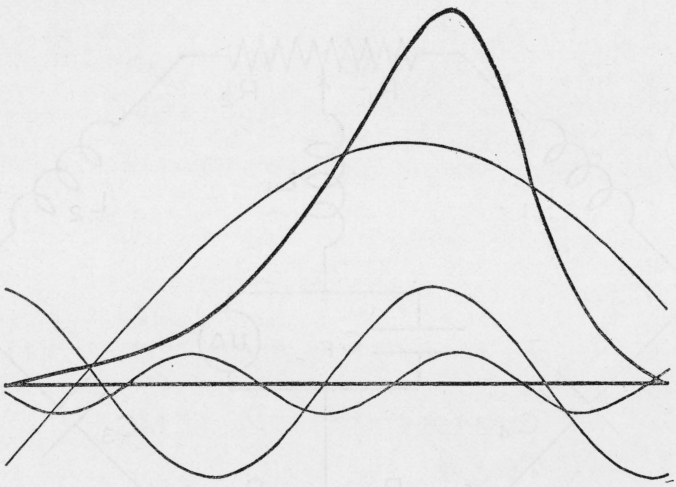

FIGURE 6.—*Wave form of magnetizing current (heavy line) and fundamental, third and fifth harmonic components.*

provision is made for comparison in terms of the third, fifth, or seventh harmonic by means of interchangeable capacitors in the filter circuit. The detector is a rectifier-type microammeter, which gives full-scale deflection for 100 microamperes. It is connected across the filter capacitor C_F, as shown. The indications of this instrument do not give the sign of the difference. This is determined by short-circuiting an auxiliary winding of a few turns on L_1. This reduces the effect of L_1, and if the reading is increased thereby, the effect of L_1 is less than that of L_2. If the reading is decreased, L_1 is the greater.

Figure 7 shows the complete instrument. In the upper left-hand corner is the ammeter and below it the dial of the autotransformer by which the current is controlled. The instrument in the middle is the microammeter. Below this instrument are the dials controlling the contacts on the slide wires. The sensitivity switch is just beneath. In the position O, the microammeter is disconnected, position H gives full sensitivity, and position L gives approximately half sensitivity. The four-point switch is the harmonic selector. By means of the other selector switches and the binding posts at the right, either an

FIGURE 7.—*Alternating-current magnetic comparator.*

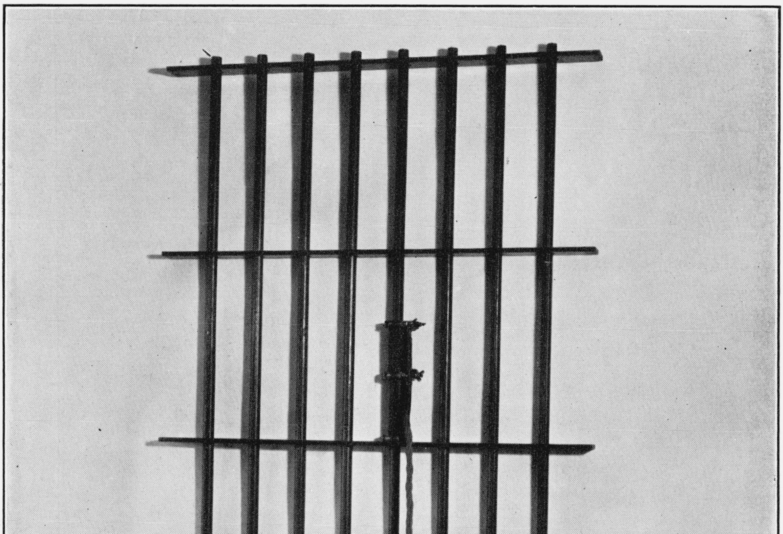

Figure 8.—*Comparator with accessory apparatus connected for testing a bar in the experimental grille.*

oscillograph or another instrument can be substituted for the micro-ammeter as the detector. The coils L_1 and L_2 are connected to the binding posts at the top and the power supply is connected to the posts at the lower left-hand corner.

IV. AUXILIARY APPARATUS

The preliminary experiments with the comparator were carried out using magnetizing coils of 200 turns. When bars are to be tested in place, however, it is not convenient to wind on so many turns. In order to obviate this difficulty, two similar transformers were constructed having a turn-ratio of 10 to 1. The high-voltage sides of these transformers are connected to the bridge and the low-voltage sides to 20-turn coils capable of carrying 40 to 50 amperes without overheating. These transformers are so nearly alike that there is no difficulty in obtaining a balance at full current when there is no iron in the test coils. Heavy twisted cable is used in making the connections on the low-voltage side. The test coil for the test specimen is of very flexible stranded wire and is wound on a split form directly on the test bar.[1] This procedure was adopted originally to avoid uncertainties in resistance which might occur if a split coil were to be used. Experience in the field has shown, however, that a split coil would be much more satisfactory if reliable contacts can be obtained.

It is important that the magnetic circuits associated with the two bars shall be as nearly alike as possible. For this reason, a yoke consisting of bars and cross pieces like those used in the actual installations was built up in which the bar used as a standard is inserted. A fixed coil surrounding the standard bar is mounted on this yoke. The auxiliary coil for determining the sign of the difference is wound on the same form. The experimental grille, comparator, and auxiliary apparatus are shown in figure 8.

V. EXPERIMENTAL RESULTS

Before taking the apparatus into the field, experiments were made to determine the best operating conditions and the range of readings to be expected for good and bad bars. Readings were made corresponding to many different combinations of bars in the experimental grille and using several different bars as standards. One of the first points considered was the best value of current to use. Readings on four bars at different values of current are plotted in figure 9. In the light of these results, 3 amperes was decided upon as a suitable value. This corresponds to about 30 amperes in the coils, or 600 ampere turns.

The question of uniformity of the bars along their length was also of interest. Wide differences were found among the bars in this respect. Typical results on four different bars are shown in figure 10. It can be seen that two of these bars are fairly uniform, but that the others show much greater variation along their length.

Experiments were made to determine the effects of using different bars as reference standards and one bar having round inserts was chosen as giving the most satisfactory results, not only for the bars

[1] Attempts were made to apply the magnetizing force by means of a yoke carrying the magnetizing winding, but it was found that there was too much variation in contact reluctance and that the properties of the oke predominated. It was necessary, therefore, to wind the coil directly on the bars.

having round inserts but also for those having square inserts. It is probable that the two types of bar are similar in composition and relative proportion of matrix and insert material. If bars of different composition are to be tested, a standard of the same kind of material and of known quality should be used.

After the preliminary tests were completed, the apparatus was tried out at the United States Industrial Reformatory at Chillicothe, Ohio, and at the United States Northeastern Penitentiary at Lewisburg, Pa.

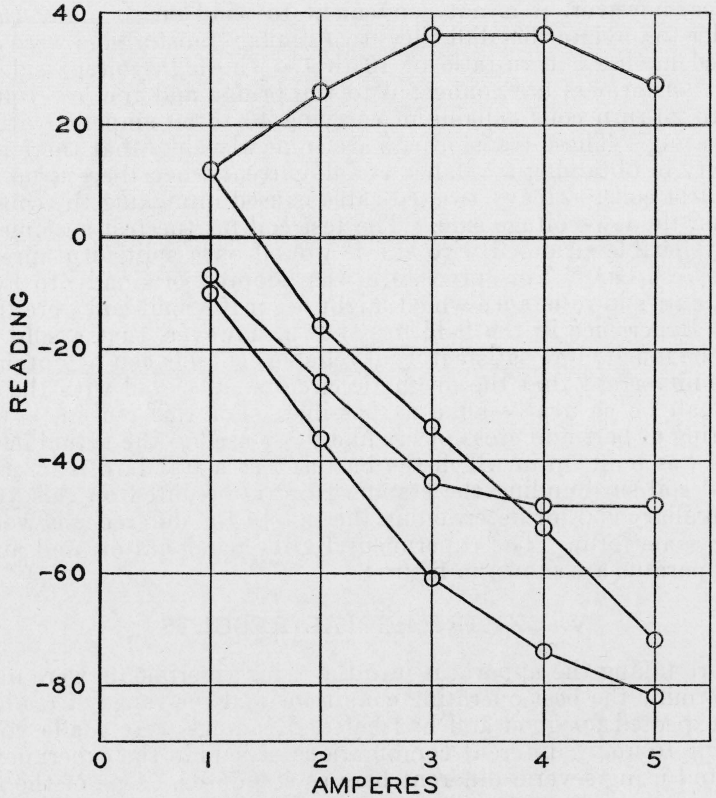

FIGURE 9.—*Relation between current and reading of the comparator for four different bars.*

At Chillicothe, drill tests had been made on a number of bars and it was thought that this would furnish an excellent opportunity to determine the reliability of the comparator. In view of tests on the experimental grille, a reading of −60 was tentatively chosen as the dividing line between good and bad bars. On this basis, bars giving a plus reading or one numerically less than 60, in the minus direction, would be considered good, and bars giving readings numerically greater than 60 in the minus direction would be considered too soft. A few of the results on the drilled bars are indicated in figure 11. If the criterion had been correctly chosen, points representing bars in which holes were drilled, indicated by circles, should all be below the −60 line and points representing bars in which no holes could be drilled, indicated by crosses, should be above the line. Points indicated by dots show results obtained at places where no drill test had been made.

At first glance the results appear to be rather disappointing. The apparent lack of correlation was explained, however, when additional drill tests were made. In general, when the comparator reading was below the −60 line, it was possible to find some place within the length covered by the test coil where a hole could be drilled com-

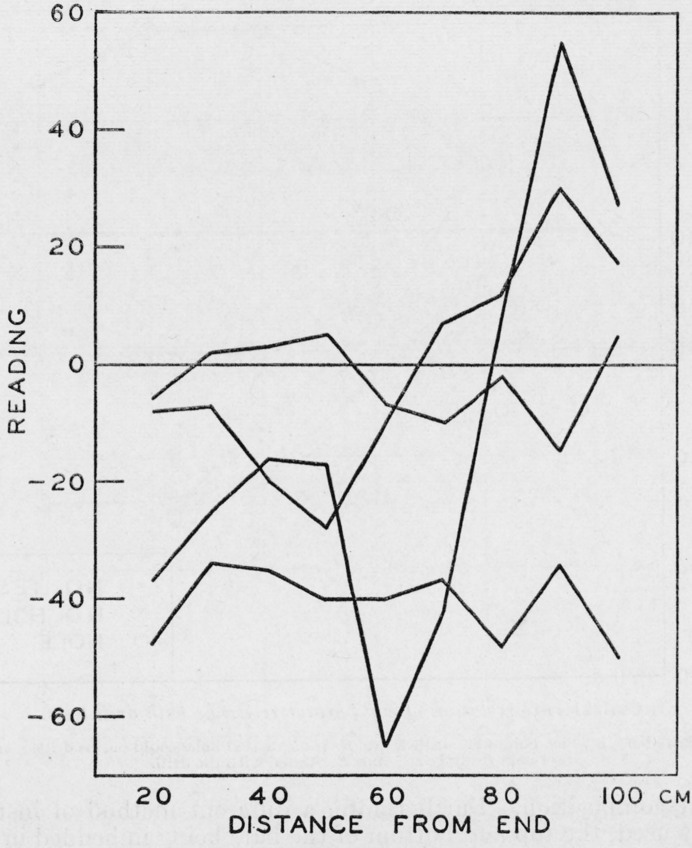

FIGURE 10.—*Degree of uniformity of four bars.*

pletely through the bar. The bars were extremely nonuniform along their length and neither the drill test nor the magnetic test could be expected to give a reliable result when applied at only one point on the bar. In some instances it was impossible to drill holes at points less than 1 inch away from holes which had been drilled, without difficulty.

A few tests were also made on bars which had been installed to replace others previously found to be unsatisfactory. Some of these were new bars with round inserts and others were bars with square inserts which had been removed, retreated, and replaced. In figure 12, the circles indicate the results obtained on the bars with round inserts and the squares show the readings for bars with square inserts. The great variation in the bars with square inserts compared with the others is evident. The large negative reading for several of the replaced bars would lead to some doubt of their quality, but in view of the fact that they were carefully inspected and tested with a drill at the plant before being installed, it may be that the standard which was used was not satisfactory for these retreated bars.

At Lewisburg, conditions were found to be quite different from those at Chillicothe. The bars are of a different type and probably have a

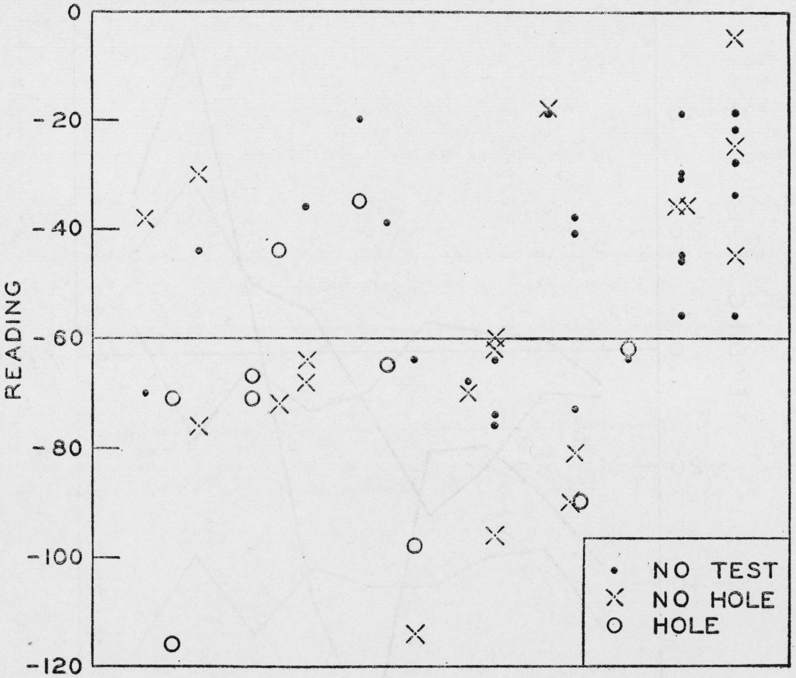

FIGURE 11.—*Correlation of comparator readings with drill tests.*

Circles indicate bars in which holes were drilled, squares indicate that holes could not be drilled, and dot represent readings at points not tested with the drill.

different composition. Furthermore, a different method of installation was used, the top and bottom of the bars being imbedded in concrete. As no similar bar known to be of satisfactory quality was available, the same standard was used as at Chillicothe. It was necessary, therefore, to compare the bars in terms of their respective readings against this standard. Two bars giving the same reading were considered to be similar. Since several of these bars had previously been found, by trial, to be satisfactorily tool-resisting, this was considered to be a safe procedure. It was also necessary to consider each group separately on account of differences in the magnetic circuits of the different kinds of grille. For each group of bars of the same diameter and having similar magnetic circuits, the readings against the standard were averaged and this average taken as normal

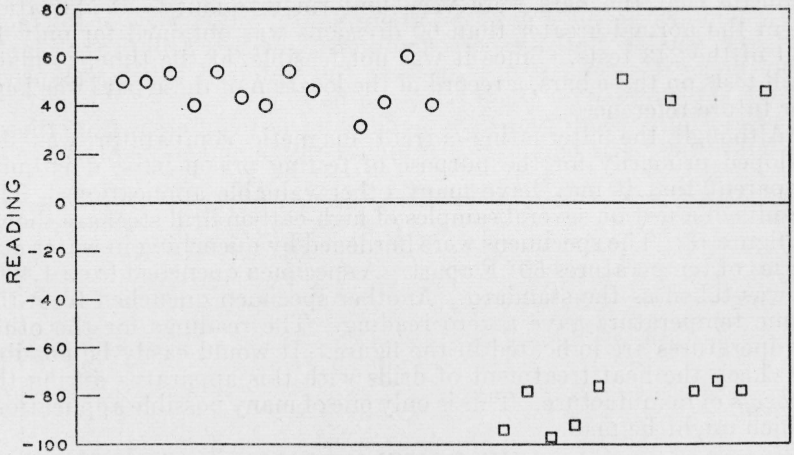

FIGURE 12.—*Results of tests on replaced bars.*

Circles represent bars with round inserts, squares represent bars with square inserts.

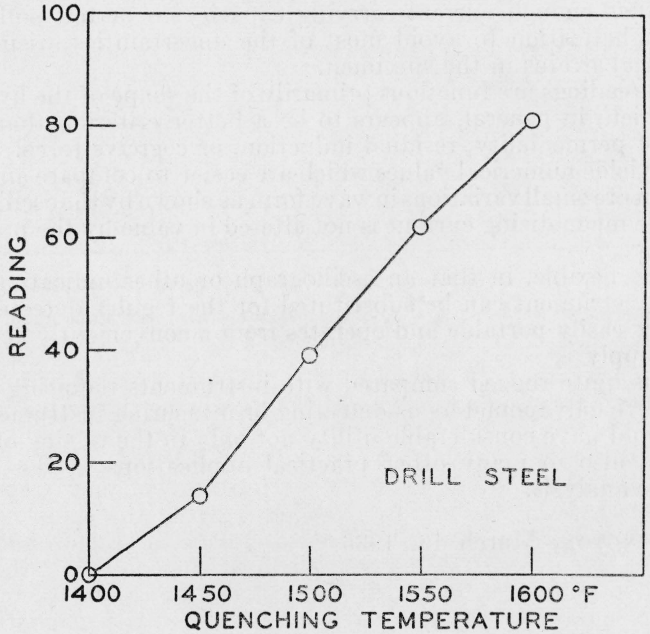

FIGURE 13.—*Relation between quenching temperature and reading on hardened drill rod.*

A specimen quenched at 1,400° F was taken as the reference standard.

for the group. The average deviation from this normal value for all bars tested was 23 scale divisions. This small deviation was taken to indicate that the bars were very uniform in quality. A deviation from the normal greater than 60 divisions was obtained for only 12 out of the 243 tests. Since it was not feasible, at the time, to make drill tests on these bars, a record of the location of these bars was kept for future reference.

Although the alternating-current magnetic comparator was developed primarily for the purpose of testing prison bars, it is quite apparent that it may have many other valuable applications. The results of a test on several samples of high-carbon drill steel are shown in figure 13. The specimens were hardened by quenching in water at a series of temperatures 50° F apart. A specimen quenched from 1,400° F was taken as the standard. Another specimen quenched from the same temperature gave a zero reading. The readings for the other temperatures are indicated in the figure. It would easily be possible to check the heat treatment of drills with this apparatus during the process of manufacture. This is only one of many possible applications which might be made.

VI. CONCLUSION

In comparison with other alternating-current methods for the application of magnetic analysis, the alternating-current magnetic comparator has several advantages.

1. It is simple and convenient to operate.
2. It has enough current-carrying capacity to permit sufficiently high magnetization to avoid most of the uncertainties arising from mechanical strains in the specimen.
3. Its readings are functions primarily of the shape of the hysteresis loop, which, in general, appears to be a better criterion than single values of permeability, residual induction, or coercive force.
4. It yields numerical values which are easier to compare and interpret than are small variations in wave form as shown by the oscillograph.
5. The magnetizing current is not altered in value by the process of balancing.
6. It is flexible, in that an oscillograph or other indicating or recording instrument can be substituted for the regular detector.
7. It is easily portable and operates from a conveniently accessible power supply.
8. It is quite rugged compared with instruments requiring the use of sensitive galvanometers as detecting or measuring instruments.

It should have considerable utility not only in the testing of prison bars but also in many other practical applications in the field of magnetic analysis.

WASHINGTON, March 13, 1936.