A CORRELATION OF SOME OF THE MECHANICAL AND MAGNETIC PROPERTIES OF SAE 4140 STEEL IN TENSION

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Jerome H. Hemmye

1955

THESIS

This is to certify that the

thesis entitled

A CORRELATION OF SOME OF THE MECHANICAL AND MAGNETIC PROPERTIES OF SAE 4140 STEEL IN TENSION

presented by

JEROME H. HEMMYE

has been accepted towards fulfillment of the requirements for

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R. T. Hinkle
Major professor

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A CORRELATION OF SOME OF THE MECHANICAL AND MAGNETIC PROPERTIES OF SAE 4140 STEEL IN TENSION

By

Jerome H. Hemmye

A THESIS

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1955

Jerome H. Hemmye

ABSTRACT

There has been little work done to relate the magnetic behavior of ferromagnetic materials with stress. This thesis is the record of the relationship found to exist between the mechanical and the magnetic behavior of SAE 4140 steel.

Standard ASTM tensile specimens were loaded and measurements were made of the resistive and inductive components of the impedance of the test coil surrounding the specimens. The final results were expressed in terms of the ratio of the initial value to the value under consideration because of the difficulty of reducing the measured values to absolute units.

The data indicate that there is a relationship between stress and the magnetic behavior of the steel. The relationship is determined by the heat treatment of the steel.

ACKNOWLEDGMENTS

The author wishes to express his sincere thanks to Doctor Rolland T. Hinkle for his encouragement and his advice. Professor Howard Womochel has given freely of his time and knowledge of Metallurgy as well as providing a wealth of advice. The original idea and approach to the problem was due to Doctor Robert Jeffries.

VITA

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INTRODUCTION

The variation of the permeability of steel when stressed has been recognized for years, having been investigated and described by Villari as early as 1864. Very little work has been done, however, on the effects of strain on the resistivity of steel.

The use of magnetic methods for the determination of the mechanical properties of steel has been suggested in the hope that a magnetic examination of the steel under stress would provide some information as to the condition or suitability of the material without destroying the part or specimen. Work done in this field, to date, has resulted in the development of metal comparators and allied devices which compare the magnetic properties of an unknown specimen with the magnetic properties of a specimen of known mechanical properties. The majority of these applications have been limited to conditions of no external stress. The work presented here has been done on standard ASTM tensile specimens with known mechanical properties in an attempt to show the results of externally applied strain on the magnetic properties of SAE 4140 Steel.

BACKGROUND

The classical techniques used for the determination of such magnetic properties of steel as permeability, magnetization, hysteresis loss and resistivity have been based on the use of direct current, 60 cps or 1,000 cps analysis. In most cases this work was done with thin laminations or very small sections with the result that the behavior of the complete cross section of the specimen was determined. The net result to date, of the work done in the past, has been adequate for magnetic circuit design and for the development of metal comparators which compare the magnetic properties of one specimen directly with those of another of known mechanical properties. The majority of these applications have been limited to conditions of no external stress.

In order to understand the behavior of a magnetic material under stress, an understanding of some of the basic theories was found to be vital. Regarding magnetostriction, Williams wrote;

> If a ferromagnetic rod shows an increase in length due to a magnetic field, that same rod will show an increase in magnetization when stretched or a decrease when compressed longitudinally. If the rod shortens in a magnetic field a corresponding Villari effect ensues. For substances which show an increase in magnetization for weak fields, and a decrease for strong fields, there is a critical field strength where the intensity is the same whether the rod is stretched or not. This is known as the Villari reversal point.[1]

Burrows extended this statement somewhat; "There is a certain value of tension for which the induction is a maximum for a given field."[2]

Many magnetic properties vary in a manner best described by the domain theory.

The modern theory of ferromagnetism attributes the ferromagnetic effects to groups of electrons called 'domains' which consist of electrons spinning on their own axes. The magnetic axes of the spinning electrons in any one domain are held parallel to each other by mutual forces known as exchange forces so that each domain behaves as a single unit. These domains account for the magneto-motive forces inherent in ferro-magnetic materials. When the material is unmagnetized, the domains are arranged in various orientations so that the total magnetic effect is zero in any direction. Under the influence of an external field the magnet axes of the domains are more or less oriented in the direction of this field, so that their effect is added to that of the applied field.[3]

These spinning electrons or spinning nucleuses have definite magnetic moments. The electron, in addition to its spin moment has a moment of momentum and a magnetic moment due to its movement in its orbit. The total magnet moment of the atom is the vector sum of all the component magnetic moments, that is, the magnetic moment of the positive charge spinning on its axis, that of the negative charge spinning on its axis and that produced by the negative charge moving in its orbit. The magnetic effect of the nucleus is of such a magnitude as to be negligible. When a rearrangement of the magnetic vectors occurs, the balance between the electric and magnetic forces is disturbed and as a result the physical dimensions can be observed to change.

These domains are assumed to be magnetically saturated areas in the ferromagnetic body. The ease or difficulty encountered in magnetizing the body is dependent upon the ease or difficulty with which these saturated domains may be rotated into the preferred direction.

Recapitulating the previous statements, the magnetic behavior of a ferromagnetic material depends on the behavior of the domains within that material. If the domain is subjected to a magnetic field it changes its dimensions in adjusting to that field and similarly if the dimensions of a domain are changed, its individual field is affected.

Footnotes

1. S. R. Williams. Journal of the Optical Society of America. Vol. 14, pp. 383-408.

2. C. W. Burrows. United States of America National Bureau of Standards Scientific Papers. Numb. 272, pp. 130.

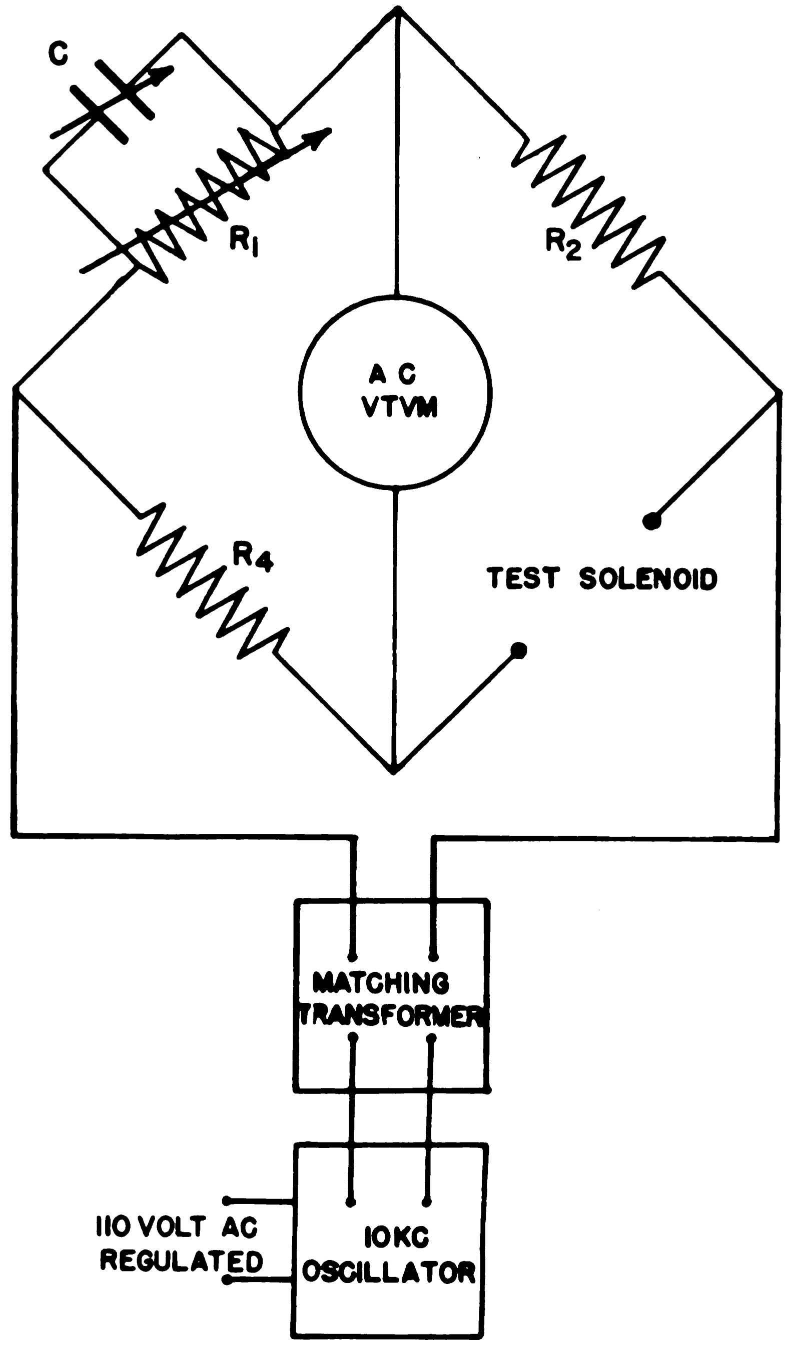
3. Present Status of Ferromagnetic Theory. Transactions of the American Institute of Electrical Engineers. Vol. 54 (1935), pp. 1251-1261.

APPARATUS AND METHODOLOGY

The first equipment constructed to measure the magnetic properties of the steel utilized a dual winding pancake type coil with the windings at right angles to each other. The initial air coupling between the coils was adjusted to a minimum and the specimen was placed in the area common to the axes of both coils. The magnetic properties were measured in relation to the effects on the mutual inductance between the two coils. Several difficulties became apparent soon after the equipment was set up. The initial air mutual was difficult to adjust to zero and because the two coils were interwound, the capacitive coupling between the windings became large enough to be prohibitive.

The second piece of equipment prepared consisted of a solenoid with two co-axial windings with a fixed value of initial mutual inductance. Again it was found that the system was impractical. The measurement of mutual inductance required a multitude of bridge manipulations, making the system unwieldy. Since relatively small changes in mutual inductance were being measured, the percentage of probable error became prohibitive and the second system was discarded.

The equipment finally used consisted of a single solenoid placed around the specimen. The inductance was measured with a Maxwell-Wein bridge. (pg.11) With the single winding supported rigidly on the specimen, it was possible to measure the inductive and resistive components of the solenoid reactance with the specimen under load.

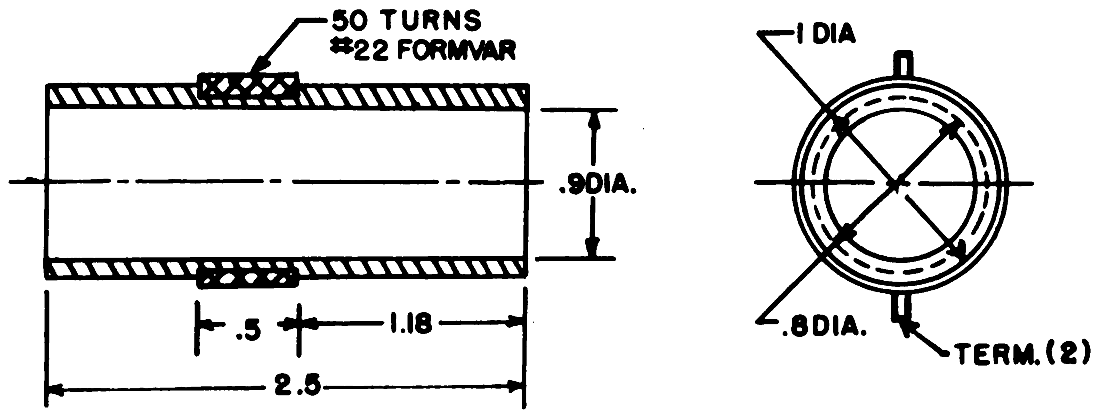


MAXWELL-WEIN BRIDGE

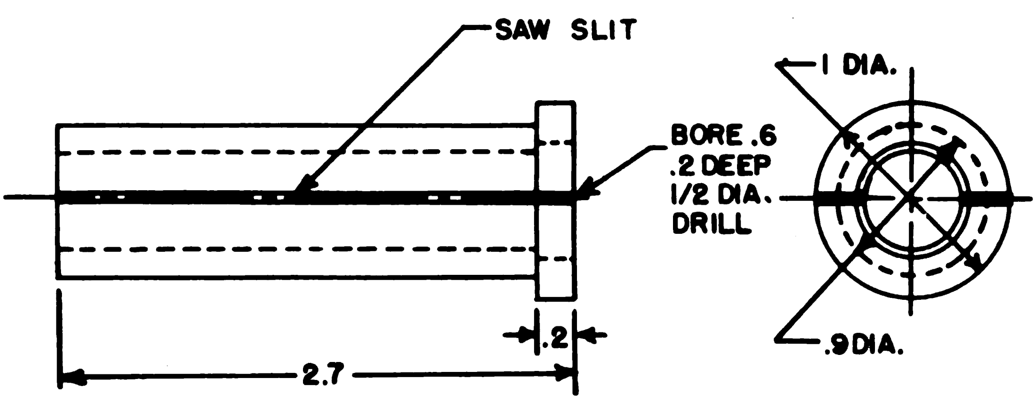
The test solenoid (pg13) was 0.5 inches long, had 50 turns of number 22 formvar wire layer wound on a bakelite spool 2.5 inches long. The inside diameter of the coil was .9 inches. The bakelite spool was designed so that it could be slid over the tensile specimen and supported rigidly on the support bushings with the solenoid directly over the reduced section of the specimen. The inductance of the test solenoid in free space was 107.29 microhenrys. The resistance at 10,000 cps was 0.30 ohms. The solenoid was connected to the bridge by a parallel rubber covered flexible cable.

The low inpedance bridge and solenoid were used to prevent, as much as possible, the influence of stray 60 cps fields on the system since the 10,000 cps field produced was itself of very small magnitude.

The passive arms of the bridge consisted of two non-inductive 10.0 ohm resistances. The adjustable arm of the bridge was a capacity decade paralleled by a resistance decade. The interconnecting wires of the bridge were made of number 10 solid copper wire to prevent any variation of the distributed capacity. The bridge galvanometer was a high impedance vacuum tube audio frequency voltmeter. The source of the 10,000 cps voltage was an audio frequency generator with a low harmonic output. The audio frequency generator had an output impedance of approximately 6000 ohms, whereas the input impedance of the bridge was approximately 10 ohms, so it was necessary to use a matching transformer between them. The matching transformer used was of oversize proportions to insure operation with a minimum of distortion introduced by the transformer.



BAKELITE FORM AND SOLENOID ASSEMBLY



BAKELITE SOLENOID SUPPORT BUSHING

Bridge Equations

Arm impedances

$$Z_1 = R_1 / 1 + j C_1 R_1 \omega$$

$$Z_2 = R_2$$

$$Z_3 = R_3 + j\omega L$$

$$Z_4 = R_4$$

For bridge balance the following equations must hold

$$\frac{Z_1}{Z_2} = \frac{Z_4}{Z_3}$$

or

$$Z_1 Z_3 = Z_4 Z_2$$

That is $$\left(\frac{R_1}{1 + j\omega C_1 R_1}\right)(R_3 + j\omega L_3) = R_2 R_4$$

$$R_1 R_3 + j\omega L_3 R_1 = R_2 R_4 + j\omega C_1 R_1 R_2 R_4$$

Separating real and imaginary terms

$$R_1 R_3 = R_2 R_4$$

and

$$L_3 R_1 = C_1 R_1 R_2 R_4$$

So that the resistive component $R = \frac{R_2 R_4}{R_1} = \frac{100}{R_1}$ ohms and the quadrature component $L = C_1 R_2 R_4 = 100 C_1$ henrys. Therefore the reactance $X = 2\pi \times 10^6 C_1$ ohms

Accuracy and Error

In making the measurements of inductance and resistance of the specimens, the capacitive bridge element had the largest calibration error and was assumed to be the only source of error since the magnitude of its deviation was of the order of 3 percent, more than 10 times the possible error of any other element. However, since the results were expressed in terms of ratios rather than in terms of absolute units, a large portion of the deviation could be expected to balance out and become negligible as was evident from the consistancy of the results.

Specimens

The specimens used in this work were first cut from a stock bar of one inch diameter SAE 4140 steel. The chemical analysis of this steel is carbon 0.373 percent, chromium 0.96 percent, molybdenum 0.21 percent and nickle a trace. The test sections were then heat treated in pairs to the desired mechanical properties, machined and the reduced sections were ground to a diameter of 0.505 inches for a distance of slightly over two inches, in accordance with the ASTM standards. In order to keep the inside diameter of the test solenoid as small as possible, the specimens were prepared with threaded ends. When completed, the specimens were aged at room temperature and away from magnetic fields for a year.

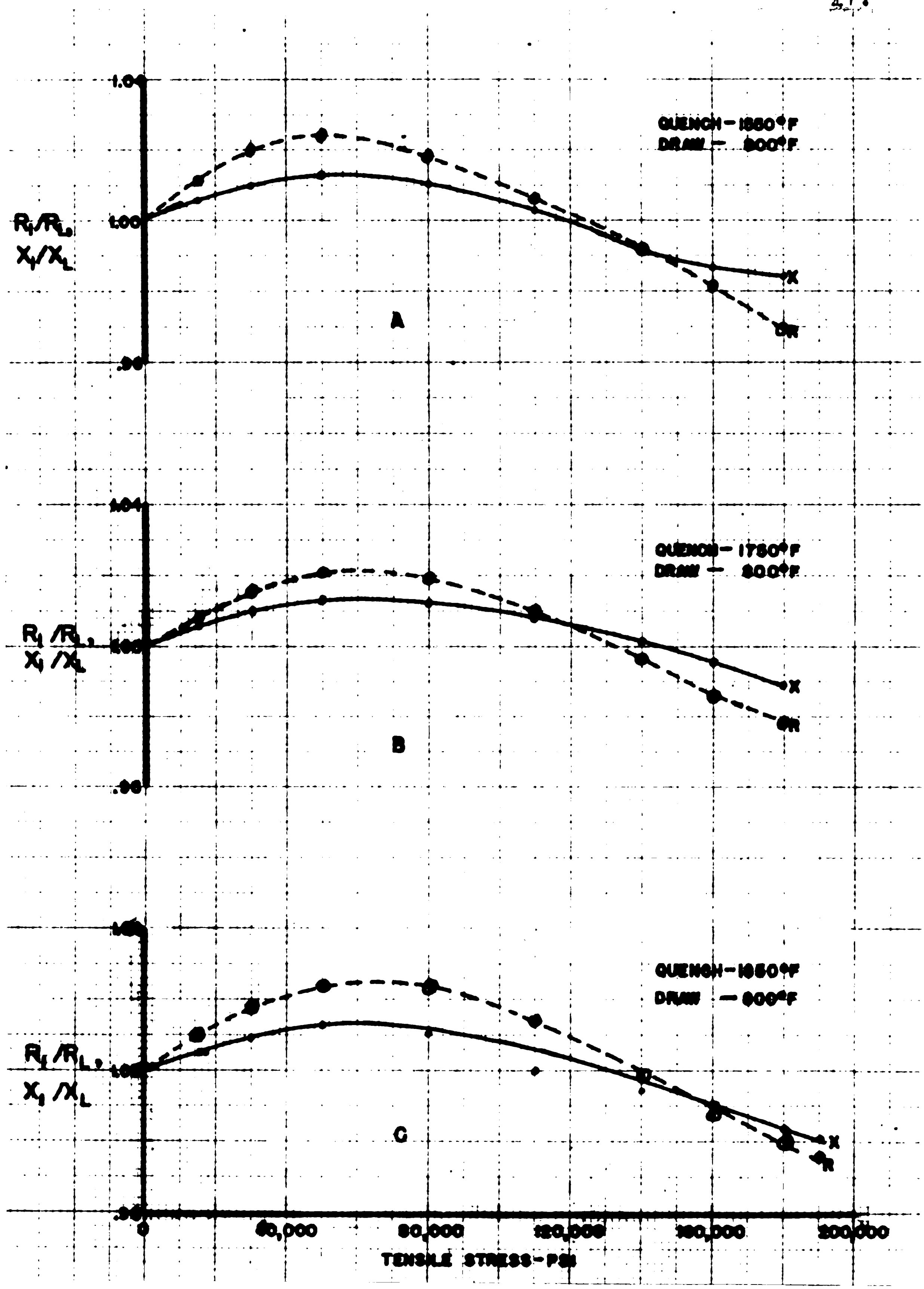
In testing the specimens, an approximate elastic limit for each was determined and the load divided into increments so that ten points on the magnetic property curves could be determined. Since the deformation beyond the elastic limit proceeded at a high rate of speed, it was impossible to determine the magnetic properties after the elastic limit had been reached.

PRESENTATION AND ANALYSIS OF DATA

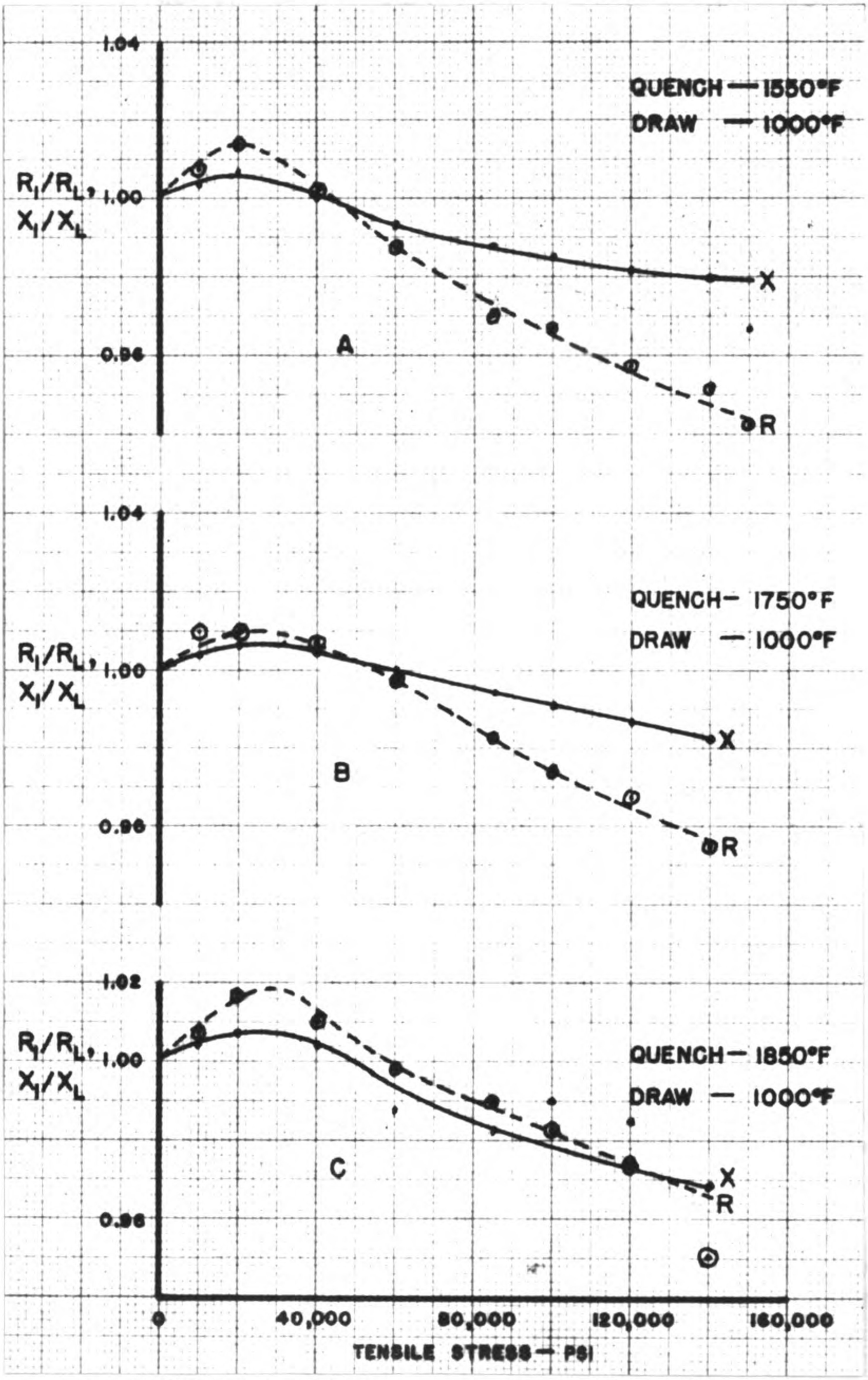
Analysis of the data for the specimens quenched from 1850 degrees F.(pg.17) indicated no significant difference from the behavior of the specimens quenched from 1750 and 1550 degrees F. An examination of the fractured sections of the specimen in which grain growth was expected showed that there had been little if any grain growth. Inasmuch as the steel used was an inherently fine grained material, this result should not have been unexpected.

The influence of the draw temperature on the magnetic properties was found to be quite pronounced. For those specimens drawn at 300 degrees F.(pg.17), there was a point on both the resistivity and inductance curves where the curves reached a maximum and then decreased in value as the load was increased. The load at which this maximum was reached seemed to lie between 50,000 and 60,000 psi. for the three quench temperatures used. The hardness on the Rockwell C scale for these specimens was between 35 and 40. As the draw temperature was increased, the tendency was for the maximum to occur at lower loads and for the curve to flatten out slightly. The maximum, which may be considered to be the Villari reversal point, for the specimens drawn at 1200 degrees appeared at approximately 25,000 psi.

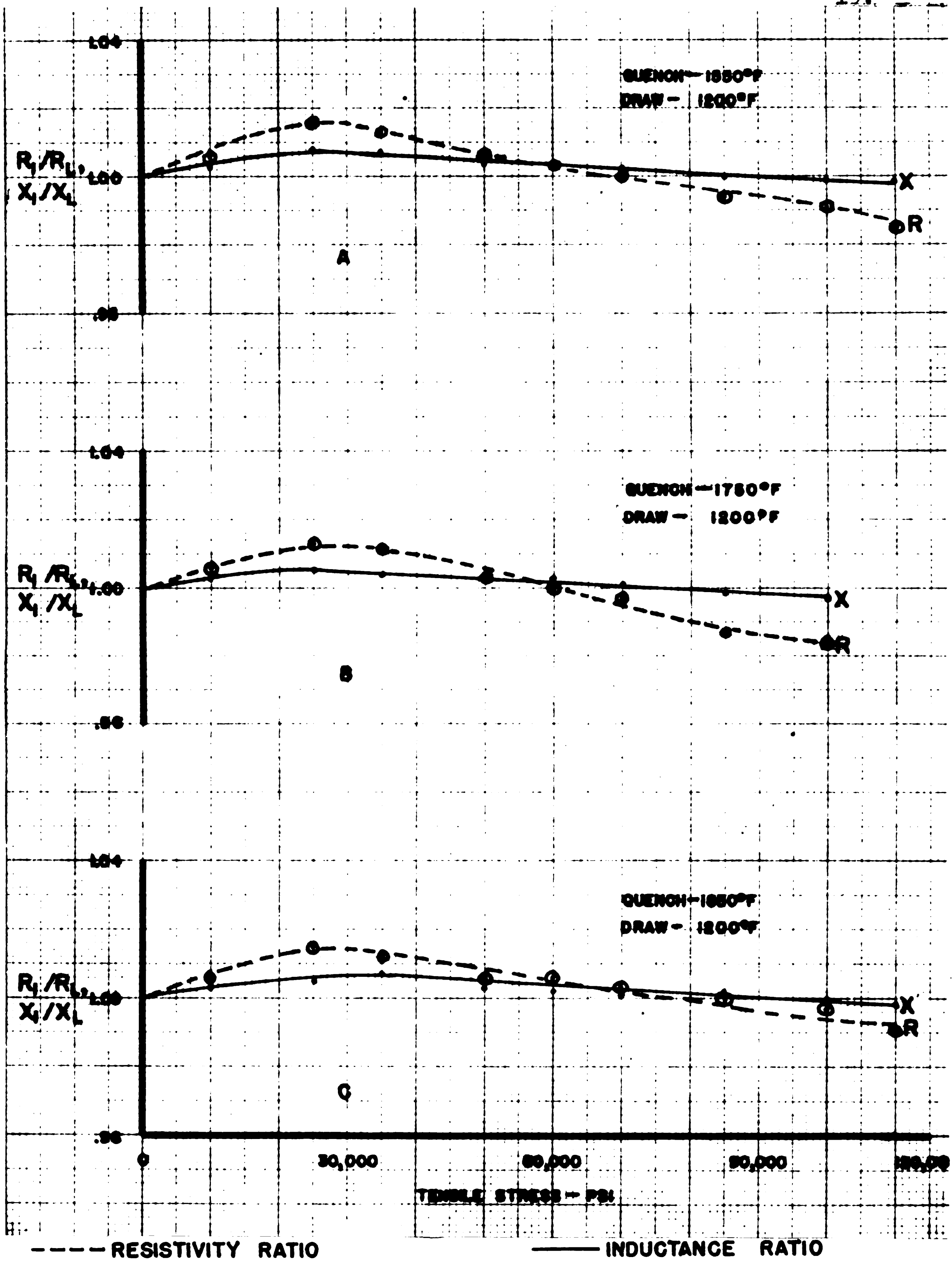
The fact that the resistivity and inductance curves passed through a Villari reversal point at approximately the same load, indicated that the rearrangement of the domains affected the resistivity as well as the permeability of the steel. The appearance of an increase in the resis-



- - - - RESISTIVITY RATIO ——— INDUCTANCE RATIO



---- RESISTIVITY RATIO ——— INDUCTANCE RATIO


1.04
QUENCH— 1550°F
DRAW— 1200°F
R_1/R_L, X_1/X_L
1.00
X
R
A
.96
1.04
QUENCH—1750°F
DRAW— 1200°F
R_1/R_L, X_1/X_L
1.00
X
R
B
.96
1.04
QUENCH—1650°F
DRAW— 1200°F
R_1/R_L, X_1/X_L
1.00
X
R
C
.96
0
30,000
60,000
90,000
TENSILE STRESS — PSI
---- RESISTIVITY RATIO
——— INDUCTANCE RATIO

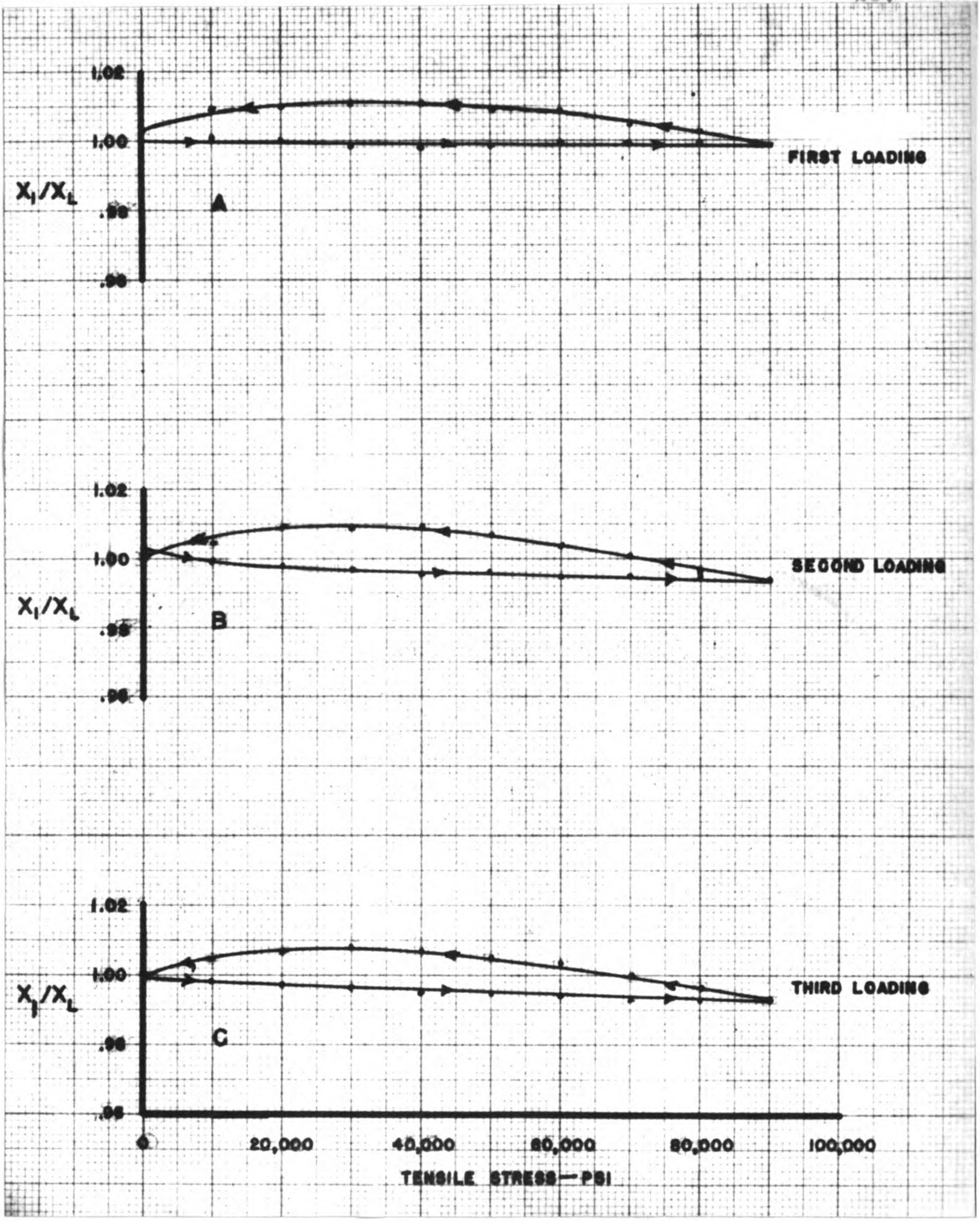
tivity as the permeability increased led to the postulation that the preferred direction for conductance in SAE 4140 steel lies at a 90 degree angle to the direction of maximum permeability within the domain. This effect was first described by Lord Kelvin in 1857.

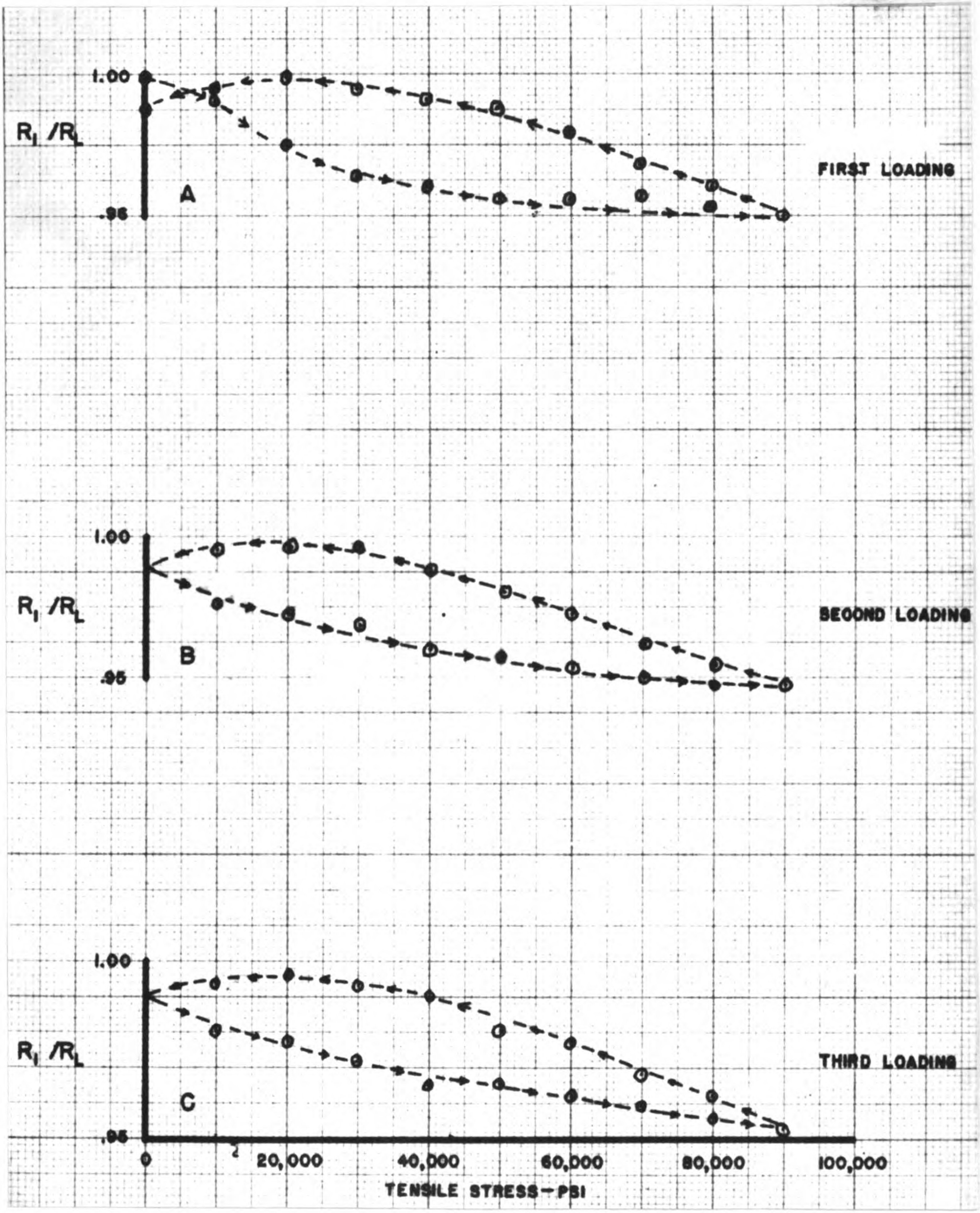
The magnetizing forces present in the test solenoid were of small enough magnitude as to be considered negligible. They were of high enough frequency so that their effect could have had little or nothing to do with the rearrangement of the domains. The changes in the properties measured could be said to be due to the effects of stress on the domains. Since the load at which the Villari reversal occurred varied with the hardness of the material and seemed to approach zero as the hardness decreased, it was felt that residual stresses in the specimens might account for the variation. To determine the effects of initial stress on the specimens, a set of specimens were fully stress relieved and cycle loaded until there was no change in the properties from one cycle to the next. These stress relieved specimens showed a steady decrease in both resistivity and permeability as the load was increased and as the tensile load was lowered, the properties increased to a maximum value and then returned to the initial value. This would indicate that the actual Villari reversal point for the material in the fully stress relieved condition was in the compressive quadrant. The reversal points on the hardened specimens would seem to be due to the initial stress on the surface of the specimen, a condition known to exist on martensite. Since the surface of the specimens was in compressive stress initially, the application of tensile stress would relieve the stress. If the Villari reversal point was located in the compressive quadrant, the material would exhibit an increase in permeability and resistivity as the compressive stress was relieved and the material passed through the Villari reversal point. Since the stress relieved specimens were not martensite but were pearlitic in nature it must be assumed that the magnetostrictive behavior of martensite and pearlite are similar for this material, for the reasoning presented to be valid. It was possible to approximate the depth of measurement of the specimen using empirical relations. Assuming a permeability of 100 and a resistivity of 10,000, the shell on which measurements were made was found to be 63 micro-inches thick. The finish of the specimens was of the order of 32 micro-inches. The major effect on the magnetic behavior was due to the surface condition and its finish.

The results arrived at in this work have been presented in terms of the ratio of the initial value measured at no external stress, to the value at the load being considered. Due to the complicated magnetic circuit, it was impossible in this case to present the absolute values of permeability and resistivity. However, since the actual values changed only a small percentage of the total value, the presentation in terms of ratios provided a very satisfactory picture of the behavior of the material.

The resistivity and permeability ratios were plotted against strain up to the elastic limit in all but one case. From the graphical presentation it was possible to analyse the effects of the mechanical properties on the magnetic properties.

Mechanical hardness, chemical composition, grain size and stress were the factors considered in relation to their effect on the magnetic properties. In the analysis, the chemical properties were controlled as closely as possible by utilizing one bar of steel from which all the specimens were cut. An attempt to control grain size was made by introducing conditions conducive to grain growth while heat treating several of the specimens. The majority of the graphs presented were arranged in quench temperature groups, since the quench temperature was the major contributing factor in grain growth in any given steel. Mechanical hardness was also controlled by proper heat treatment. The draw temperature was varied from that necessary to give the highest practical hardness to that value necessary to give a relatively soft condition. It was found that some factor was not being controlled in the specimens and in an attempt to discover if the initial stress due to machining or quenching was causing the variation from the results expected, a series of specimens were stress relieved. No machining operations were performed on these specimens after stress relieving them. They were not loaded in the same manner as the previous specimens but were instead taken through a series of load and unload cycles.


1.02
1.00
X_1/X_L
.98
.96
A
FIRST LOADING
1.02
1.00
X_1/X_L
.98
.96
B
SECOND LOADING
1.02
1.00
X_1/X_L
.98
.96
C
THIRD LOADING
0
20,000
40,000
60,000
80,000
100,000
TENSILE STRESS—PSI


1.00
R_1/R_L
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FIRST LOADING
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SECOND LOADING
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C
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THIRD LOADING
0
20,000
40,000
60,000
80,000
100,000
TENSILE STRESS—PSI

SUMMARY AND CONCLUSIONS

The influence of the mechanical properties on the magnetic properties of SAE 4140 steel were pronounced and to a certain degree predictable if compared with the properties of a similar material. The temperature from which the material was quenched had little effect on the overall behavior so that it would seem possible in certain controlled situations to utilize the magnetic behavior in the determination of the mechanical condition of a specimen.

The influence of initial stress on the specimen was found to be quite significant. Since the magnetic examination was made to a depth of only 62 micro-inches, the surface stress determined the behavior of the magnetic properties. Having recognized the fact that martensite in formation tended to develop compressive stress on the surface, a set of specimens fully stress relieved were examined and evaluated. The results of that evaluation indicated that the load at which the permeability and resistivity reached a maximum was actually a compressive load, in spite of the fact that the reversal point occured in tension in the martensitic specimens. (pg.22-24)

The use of magnetic analysis methods for specimens or materials under stress would seem to be feasible under certain circumstances. An accurate analysis of results obtained from a magnetic analysis would require considerable knowledge about the loading, making use of the method something short of practical for ordinary testing of materials. However, since the use of a high frequency technique limited the field penetration, it would seem logical to apply the methods presented here for the measurement of superficial stresses on the surface of the material in question, a difficult process using any other method.

It was assumed in this work that the magnetic properties of pearlitic steel were the same as the magnetic properties of austenitic steel. This is not entirely the case. An investigation of the behavior of a series of pearlitic specimens heat treated to the same hardness as the specimens used in this work would be of considerable value.

Further work in this field should be done since the effects of shear stress, direct compressive stress, and the effects of machining were not completely investigated. A series of tests made on torsion specimens would help establish the influence of shear stress on the magnetic behavior. Further verification of the location of the Villari reversal point should be obtained from a series of compressive tests. The influence of machining or surface finish could be determined while running the compressive tests. The specimens heat treated should be in a semi-finished condition to eliminate as much as possible the influence of machining stresses, and to allow closer correlation between the quenched condition and mechanical properties.

APPENDIX

LOAD LB	STRESS PSI	R Ω	L μhy	X Ω	Ro/R	Xo/X
0	0	3.5088	162.82	10.230	1.0	1.0
3,000	15,000	3.5461	163.72	10.287	1.011	1.006
6,000	30,000	3.5714	164.29	10.323	1.019	1.009
10,000	50,000	3.5971	164.89	10.360	1.025	1.013
16,000	80,000	3.5714	164.39	[illegible] 329	1.018	1.0[illegible]0
22,000	110,000	3.5336	163.52	10.274	1.007	1.004
28,000	140,000	3.4843	161.44	10.144	.993	.992
32,000	160,000	3.4483	161.34	10.137	.983	.991
36,000	180,000	3.4014	160.35	10.075	.969	.985

QUENCH – 1550°F, DRAW – 800°F

LOAD LB	STRESS PSI	R Ω	L μhy	X Ω	Ro/R	Xo/X
0	0	3.4965	162.03	10.181	1.0	1.0
3,000	15,000	3.5211	162.93	10.237	1.007	1.006
6,000	30,000	3.5461	163.62	10.281	1.014	1.010
10,000	50,000	3.5714	164.29	10.323	1.021	1.014
16,000	80,000	3.5587	164.2[illegible]	10.31[illegible]	1.018	[illegible]13
22,000	110,000	3.5336	163.52	10.274	1.011	1.[illegible]09
28,000	140,000	3.4843	162.52	10.212	.997	1.003
32,000	160,000	3.4483	161.63	10.155	.986	.997
36,000	180,000	3.4247	160.74	10.100	.979	.992

QUENCH – 1750°F, DRAW – 800°F

LOAD LB	STRESS PSI	R Ω	L μhy	X Ω	Ro/R	Xo/X
0	0	3.3445	159.36	10.012	1.0	1.0
3,000	15,000	3.3784	160.05	10.056	1.010	1.004
6,000	30,000	3.4014	160.84	10.106	1.017	1.009
10,000	50,000	3.4247	161.44	10.144	1.024	1.013
16,000	80,000	3.4247	161.13	10.124	1.024	1.011
22,000	110,000	3.3898	159.31	10.010	1.014	1.000
28,000	140,000	3.3333	158.56	9.963	.997	.995
32,000	160,000	3.3113	157.97	9.926	.990	.991
36,000	180,000	3.2787	156.88	9.857	.980	.985
38,000	190,000	3.2680	156.38	9.826	.977	.981

QUENCH - 1850°F, DRAW - 800°F

LOAD (LB)	STRESS (PSI)	R (Ω)	L (μH)	X (Ω)	Ro/R	Xo/X
0	0	3.3784	157.67	9.907	1.0	1.0
2,000	10,000	3.4014	158.27	9.944	1.007	1.004
4,000	20,000	3.4247	158.56	9.963	1.014	1.006
8,000	40,000	3.3784	157.57	9.900	1.000	.999
12,000	60,000	3.3333	156.58	9.838	.987	.993
17,000	85,000	3.2787	155.98	9.800	.970	.989
20,000	100,000	3.2680	155.68	9.782	.967	.987
24,000	120,000	3.2362	154.99	9.738	.958	.983
28,000	140,000	3.2154	154.59	9.713	.952	.980
30,000	150,000	3.1847	152.54	9.584	.943	.967

QUENCH - 1550°F , DRAW - 1000°F

LOAD (LB)	STRESS (PSI)	R (Ω)	L (μH)	X (Ω)	Ro/R	Xo/X
0	0	3.3557	157.57	9.900	1.0	1.0
2,000	10,000	3.3989	158.27	9.944	1.010	1.004
4,000	20,000	3.3898	158.56	9.963	1.010	1.006
8,000	40,000	3.3784	158.27	9.944	1.00[illegible]	1.004
12,000	60,000	3.3446	157.47	9.894	.997	.993
17,000	85,000	3.3003	156.68	9.845	.983	.994
20,000	100,000	3.2680	156.19	9.814	[illegible]	.991
24,000	120,000	3.2468	155.58	9.775	.968	987
28,000	14,000	3.2851	154.79	9.726	.955	982

QUENCH - 1750°F , DRAW - 1000°F

LOAD LB	STRESS PSI	R Ω	L μhy	X Ω	Ro/R	Xo/X
0	0	3.3557	157.08	9.870	1.0	1.0
2,000	10,000	3.3784	157.67	9.907	1.007	1.004
4,000	20,000	3.4130	158.27	9.944	1.017	1.007
8,000	40,000	3.3898	157.77	9.913	1.010	1.004
12,000	60,000	3.3445	155.22	9.753	.997	.988
17,000	85,000	3.2895	154.41	9.703	.980	.983
20,000	100,000	3.2680	155.48	9.769	.974	.990
24,000	120,000	3.2362	154.79	9.726	.964	.985
28,000	140,000	3.1897	152.24	9.565	.949	.969

QUENCH - 1850°F , DRAW - 1000°F

$LOAD_{LB}$	$STRESS_{PSI}$	R Ω	$L_{\mu hy}$	X Ω	Ro/R	Xo/X
0	0	3.1250	150.46	9.454	1.0	1.0
2,000	10,000	3.1447	150.95	9.484	1.006	1.003
5,000	25,000	3.1716	151.64	9.528	1.016	1.008
7,000	35,000	3.1646	151.45	9.516	1.013	1.007
10,000	50,000	3.1447	151.05	9.491	1.006	1.004
12,000	60,000	3.1348	160.95	9.484	1.003	1.003
14,000	70,000	3.1260	150.75	9.472	1.000	1.002
17,000	85,000	3.1056	150.46	9.454	.994	1.000
20,000	100,000	3.0960	150.36	9.447	.991	.999
22,000	110,000	3.0769	150.26	9.441	.985	.999

QUENCH - 1550°F , DRAW - 1200°F

$LOAD_{LB}$	$STRESS_{PSI}$	R Ω	$L_{\mu hy}$	X Ω	Ro/R	Xo/X
0	0	3.1746	150.36	9.447	1.0	1.0
2,000	10,000	3.1949	150.75	9.472	1.006	1.003
5,000	25,000	3.2154	151.05	9.491	1.013	1.005
7,000	35,000	3.2051	150.95	9.484	1.010	1.004
10,000	50,000	3.1847	150.85	9.478	1.003	1.003
12,000	60,000	3.1746	150.75	9.472	1.000	1.003
14,000	70,000	3.1646	150.55	9.459	.997	1.001
17,000	85,000	3.1348	150.16	9.435	.987	.999
20,000	100,000	3.1250	149.96	9.422	.984	.997

QUENCH - 1750°F , DRAW - 1200°F

LOAD (LB)	STRESS (PSI)	R (Ω)	L (μH)	X (Ω)	Ro/R	Xo/X
0	0	3.0395	147.78	9.285	1.0	1.0
2000	10,000	3.0581	148.18	9.3[illegible]	1.006	1.003
5000	25,000	3.0864	148.57	9.33[illegible]	1.[illegible]15	1.005
7000	35,000	3.0769	148.87	9.354	1.012	1.007
10,000	50,000	3.0581	148.18	9.310	1.006	1.003
12,000	60,000	3.0581	148.08	9.304	1.006	1.002
14,000	70,000	3.0488	147.98	9.298	1.003	1.001
17,000	85,000	3.0395	147.98	9.298	1.003	1.001
20,000	100,000	3.0303	147.78	9.285	.999	1.[illegible]00
22,000	110,000	3.0120	147.48	9.266	.991	.998

QUENCH - 1850°F , DRAW - 1200°F

LOAD LB	STRESS PSI	R Ω	L μH	X Ω	Ro/R	Xo/X
0	0	3.205	148.97	9.360	1.0	1.0
2,000	10,000	3.185	149.17	9.373	.994	1.001
4,000	20,000	3.145	148.97	9.360	.981	1.000
6,000	30,000	3.115	148.67	9.341	.972	.998
8,000	40,000	3.106	148.67	9.341	.969	.998
10,000	50,000	3.096	148.67	9.341	.966	.998
12,000	60,000	3.096	148.77	9.347	.966	.999
14,000	70,000	3.096	148.87	9.354	.966	.999
16,000	80,000	3.086	148.77	9.347	.963	.999
18,000	90,000	3.077	148.67	9.341	.960	.998
16,000	80,000	3.106	149.47	9.391	.969	1.003
14,000	70,000	3.125	149.76	9.410	.975	1.005
12,000	60,000	3.155	150.26	9.441	.984	1.009
10,000	50,000	3.175	150.36	9.447	.991	1.009
8,000	40,000	3.185	150.55	9.459	.994	1.011
6,000	30,000	3.195	150.56	9.460	.997	1.011
4,000	20,000	3.205	150.46	9.454	1.000	1.010
2,000	10,000	3.195	150.26	9.441	.997	1.009
0	0	3.175	149.37	9.385	.991	1.003

STRESS RELIEVED ~ RUN #1

LOAD LB	STRESS PSI	R Ω	L μhy	X Ω	Ro/R	Xo/X
0	0	3.175	149.37	9.385	.991	1.003
2,000	10,000	3.145	148.87	9.364	.981	.999
4,000	20,000	3.138	148.67	9.341	.979	.998
6,000	30,000	3.125	148.57	9.335	.975	.997
8,000	40,000	3.106	148.38	9.323	.969	[illegible]
10,000	50,000	3.096	148.38	9.323	.966	.996
12,000	60,000	3.086	148.28	9.317	.963	.995
14,000	70,000	3.077	148.18	9.310	.960	.995
16,000	80,000	3.067	148.18	9.310	.957	.995
18,000	90,000	3.067	148.08	9.304	.957	.994
16,000	80,000	3.086	148.47	9.329	.963	.997
14,000	70,000	3.106	149.07	9.366	.969	1.001
12,000	60,000	3.135	149.56	9.397	.978	1.004
10,000	50,000	3.155	150.06	9.429	.984	1.007
8,000	40,000	3.175	150.26	9.441	.991	1.009
6,000	30,000	3.195	150.35	9.447	.997	1.009
4,000	20,000	3.195	150.26	9.441	.997	1.009
2,000	10,000	3.195	149.76	9.410	.997	1.005
0	0	3.175	149.17	9.373	.991	1.007

STRESS RELIEVED ~ RUN #2

LOAD lb	STRESS psi	R Ω	L μhy	X Ω	Ro/R	Xo/X
0	0	3.175	149.17	9.373	.991	1.001
2,000	10,000	3.145	148.67	9.341	.981	.998
4,000	20,000	3.135	148.57	9.335	.978	.997
6,000	30,000	3.115	148.38	9.323	.972	.996
8,000	40,000	3.096	148.18	9.310	.966	.995
10,000	50,000	3.096	148.18	9.310	.966	995
12,000	60,000	3.086	148.08	9.304	.963	.994
14,000	70,000	3.077	147.98	9.298	.960	.993
16,000	80,000	3.067	147.98	9.298	.957	.993
18,000	90,000	3.058	147.88	9.292	.954	.993
16,000	80,000	3.086	148.38	9.323	.963	.996
14,000	70,000	3.106	148.97	9.360	.969	1.00
12,000	60,000	3.135	149.56	9.397	.978	1.004
10,000	50,000	3.145	149.76	9.410	.981	1.005
8,000	40,000	3.175	150.06	9.429	.991	1.007
6,000	30,000	3.185	150.16	9.435	.994	1.008
4,000	20,000	3.195	150.06	9.429	.997	1.007
2,000	10,000	3.185	149.66	9.403	.994	1.005
0	0	3.175	149.17	9.373	.991	1.001

STRESS RELIEVED ~ RUN #3