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MAGNETIC PERMEABILITY AND MECHANICAL
PROPERTY MEASUREMENTS ON VARIOUS
COLD WORKED STATES OF 316
STAINLESS STEEL

M. W. Poore

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OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

prepared for the U.S. ATOMIC ENERGY COMMISSION
under U.S. GOVERNMENT Contract W-7405 eng 26

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**MAGNETIC PERMEABILITY AND MECHANICAL PROPERTY
MEASUREMENTS ON VARIOUS COLD WORKED
STATES OF 316 STAINLESS STEEL**

M. W. Poore

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Oak Ridge Y-12 Plant

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This report is based on a study by the author as partial fulfillment of requirements for the degree of Master of Science in Physics from The University of Tennessee.

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ABSTRACT

A detailed analysis has been made on 316 stainless steel to determine the effects of cold working on the magnetic permeability and the mechanical properties of the material. After initially characterizing the material, it was cold worked by rolling to several states of cold reduction. These states were approximated in 10% increments from 0% to 50% cold reduction. The mechanical properties of each state were fully determined parallel and perpendicular to the rolling direction. Specimens from each cold reduced state were also cold worked by tensile deformation. The relative permeability change measured, using an eddy current phase sensing technique, was determined for the two forms of cold work and their various combinations. Cold working by rolling only was found to give a larger increase in surface permeability than cold working by tensile deformation. The combination of these two forms of cold work particularly at 30%, 40%, and 50% cold reduced levels gave the largest increases in permeability. The maximum increase in relative permeability was approximately 4500 ppm which occurred in the necked portion of a 50% cold reduced specimen which had undergone 7.5% tensile elongation. In the mechanical properties of the material, an increase was noted in the tensile strength of approximately 85% for the longitudinal and 98% for the transverse tensile specimens taken from the range of 0% to 50% cold reduction.

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CHAPTER I

INTRODUCTION

The use of 316 stainless steel in reactor technology has been extensive over the last few years. Part of this interest is due to the ability of cold worked 316 stainless steel to withstand intense nuclear irradiation without large amounts of swelling due to void formation (Straalsund and Brager, 1971). This ability, along with cold working to give the desired mechanical properties, has given 316 stainless steel certain advantages over the more conventional stainless steels.

The 316 stainless steel is a weakly ferromagnetic material which, when subjected to cold work, undergoes some transformation from a paramagnetic austenite (gamma phase) to a ferromagnetic alpha martensite (Breinan and Ansell, 1970). The purpose of this research is to fully study and measure the small magnetic permeability changes which occur in this material for various cold worked states. It is hoped that this research will then describe a successful nondestructive technique for measuring the worked condition of 316 stainless steel.

Because of the effect of certain elements as austenite stabilizers, correlation between cold working and magnetic permeability is very dependent on the composition of the steel which can vary widely among lots. For this reason, the 316 stainless steel used in this research was extensively analyzed mechanically and chemically.

The permeability was measured using a phase sensitive eddy current technique as developed by Dodd (1968) which is accurate in measurement of relative permeability to ± 50 ppm.

An effort was made in this research to compare the cold working caused by tensile deformation and that due to rolling. The cold working due to tensile deformation was the more controlled operation in that the temperature was closely observed and the crosshead speed was constant.

CHAPTER II

THEORY

I. PRINCIPLE OF PHASE SENSING

Though the eddy current solenoidal coil does not produce a plane wave, the concept of phase sensitive eddy current measurement may be simply demonstrated by considering an electromagnetic plane wave striking the boundary of a conducting medium at normal incidence. A portion of the wave is reflected, and the remainder enters the conducting medium. Using the differential form of Maxwell's equation as derived from Ampere's law:

$$(1) \quad \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t},$$

and the differential form of Maxwell's equation as derived from Faraday's law:

$$(2) \quad \nabla \times \vec{E} = - \frac{\partial \vec{B}}{\partial t},$$

the equation for a linearly polarized wave entering the conducting medium in the x direction with $\vec{E}$ in the y direction is:

$$(3) \quad \frac{1}{\mu} \frac{\partial^2 E_y}{\partial x^2} - \epsilon \frac{\partial^2 E_y}{\partial t^2} - \sigma \frac{\partial E_y}{\partial t} = 0$$

For a conductor in the lower frequency range as is the case of this study, the second term of equation (3) is negligible and reduces to:

$$(4) \quad \frac{1}{\mu} \frac{\partial^2 E_y}{\partial x^2} - \sigma \frac{\partial E_y}{\partial t} = 0$$

A solution of this wave equation for a wave traveling in the positive X direction is given by:

$$(5) \quad E_y = E_o e^{(j\omega t - \gamma x)}$$

where:

$$(6) \quad \gamma^2 = j\omega\mu\sigma$$

Substituting equation (6) into (5), we obtain:

$$(7) \quad E_y = E_o e^{-\left(\frac{\omega\mu\sigma}{2}\right)^{1/2} x} e^{j\omega t} e^{-j\left(\frac{\omega\mu\sigma}{2}\right)^{1/2} x}$$

A similar solution may be obtained for the wave equation:

$$(8) \quad \frac{1}{\mu} \frac{\partial^2 H_z}{\partial x^2} - \sigma \frac{\partial H_z}{\partial t} - \epsilon \frac{\partial^2 H_z}{\partial t^2} = 0$$

Therefore, one can see from equation (7) that the amplitude of the wave in a conductor is attenuated exponentially with distances; whereas, the phase is a linear function of thickness (Kraus, 1953).

II. PHASE SENSING MEASUREMENT

In the through transmission phase sensitive measurement technique, a transmitter coil produces an electromagnetic field which enters the conductor. A portion of this field is transmitted through the conductor and detected by a voltage induced in a receiver coil (Dodd, 1972). The phase shift between the transmitted and received voltage is then measured. As can be seen in equation (7), changes in the thickness of a conductor produce linear phase shift.

In the reflection phase sensitive measurement technique, the entire inductance balance system is placed in a probe. The probe contains a large driver coil which produces the field.

The reflected field is measured by two small pickup coils which are coaxially positioned within the probe and wound in opposite directions. This arrangement is shown in Figure 1 (Dodd, Deeds, Luquire, Spoeri, 1969). If in air, the net signal received by the pickup coils is zero. When the probe is brought near a conductor, the pickup coil nearest the conductor detects the reflected wave produced from the field of the driver and the other pickup hardly perceives the reflected wave because of attenuation of the field. Thus, accurate phase shift is measured between the driver voltage and the pickup voltage (Dodd, 1968). The net voltage induced in the pickup is:

$$(9) \quad V = V_{pu_2} - V_{pu_1}.$$

The theoretical basis of the voltage and phase induced in the reflection coil was developed by Dodd and Deeds (1968), and is of the form:

$$(10) \quad V = \frac{j\omega\mu_0 n n' I \bar{r}}{(r_2 - r_1)(r_4 - r_3) L_2 L_6} \int_0^{\infty} \frac{1}{\alpha^6} J(r_2, r_1) J(r_4, r_3) e^{-2\alpha L} \\ \times \left[e^{-\alpha(L_2 - 2L_5 - L_6)} - 1 \right] \left[e^{-\alpha L_5} - e^{-\alpha(L_6 + L_5)} \right] \left[1 - e^{-\alpha L_2} \right] \\ \times \left[\frac{(\alpha + \beta_1)(\beta_1 - \beta_2) + (\alpha - \beta_1)(\beta_1 + \beta_2) e^{2\alpha_1 c}}{(\alpha - \beta_1)(\beta_1 - \beta_2) + (\alpha + \beta_1)(\beta_1 + \beta_2) e^{2\alpha_1 c}} \right] d\alpha.$$

Definitions of the symbols used are given in Appendix A.

Figure 1. The reflection type eddy current probe above a two conductor plane.

CHAPTER III

EXPERIMENTAL MEASUREMENTS AND EVALUATIONS

I. INITIAL MATERIAL EVALUATION

Procurement of Plate

A single plate of 316 stainless steel was received from the Sandmeyer Steel Company. The plate was approximately 5/16 inches thick and about 60 inches by 36 inches in dimensions. The heat lot number was 114682.

Chemical Analysis

Because the chemical composition of the 316 stainless steel plate is very important in correlating to analysis already available, it was necessary to run a chemical analysis to assure that the vendor had met the composition limits specified in Table I (see Appendix B).

The Y-12 chemical analysis showed the carbon and nitrogen to be above and the nickel to be below the limits specified. All three of these elements are thought to be austenite stabilizers (Cina, 1954). Because of the great importance of nickel in stabilizing the austenite, three more chemical analyses were run for nickel content only. The average of these three were then used. The results of the Y-12 analysis and that of the vendor are given in Table I.

Mechanical and Metallographic Analysis

The plate, as received from the vendor, was machined into 14 smaller plates to dimensions approximated in Figure 2. These plates

Figure 2. Cutting schedule for large steel plate with smaller plates marked in the direction they are to be rolled.

were identified by number and marked in the direction they would be cold rolled.

Because of the importance that these plates all be in the annealed condition before rolling, a mechanical properties and micro-examination of the material was made.

The mechanical properties examination consisted of machining tensile specimens with a gage length of one inch and a width of 0.25 inches from the plate identified as number 1. Two sets of five specimens were machined with each set perpendicular to the other. The purpose of this was to reveal any anisotropy, that is, differences in the mechanical properties which would result had cold working operations such as rolling been introduced into the material (Lubahn and Felgar, 1961).

The results of these tests are given in Table II (see Appendix B). Had there been cold working of the material by even small amounts, there should be a considerable difference in the yield strength of the two sets of specimens. This does not appear to be the case.

The vendor supplied mechanical properties are given in Table III (see Appendix B).

A metallographic examination was also conducted on the material prior to rolling. This examination consisted of machining one 1/2 X 1/2 inch micro specimen from each of three plates. The specimens were then mounted and etched to enable micro-examination of the grain structure. The micro-examination showed no indication of work condition. Micro-hardness tests were also conducted on the specimens. The results of these are given in Table IV (see Appendix B).

II. EVALUATION OF COLD WORKED PLATES

Cold Working by Rolling

Plates number 9 through number 13 were cold rolled on a fourteen inch rolling mill to cold reduced state of 10% to 50% reduction in thickness in approximate increments of 10%. Plate number 8 was kept in the "as received" condition.

Preliminary thickness measurements were made around each plate before rolling. Final measurements after rolling were made on the large tensile specimens described later. Table V (see Appendix B) shows the final and initial thickness averages as well as the calculated percent reduction of thickness.

Several passes through the rolling mill were made on each of the rolled plates. The number of passes depended on the percent reduction desired. Each pass was believed to have reduced the thickness between 10 and 20 mils. This increment became smaller as the plate became harder due to the cold working effect.

The temperature of the room and the plates was not measured during rolling, but it is estimated that the last two plates might have reached between 200°F and 300°F because they had to be handled with work gloves during rolling. Careful rolling of the plates was not adequate to prevent the curving of plate numbers 11 and 13.

Machining of Plates

Plate numbers 8 through 13 were machined according to the cutting schedule shown in Figure 3. In the case of plate numbers 11 and 13, the least curved sections were used.

Figure 3. Specimen cutting schedule for each of the plates.

Legend:

- Specimens 1 through 5: Small tensile specimens parallel to rolling direction.
- Specimens 6 through 10: Small tensile specimens perpendicular to rolling direction.
- Specimen 11 through 15: Large tensile specimen, perpendicular to rolling direction.
- Specimen 16 through 20: Large tensile specimens, parallel to rolling direction.
- Specimen 21: The square plate used for eddy current measurements.

The cutting schedule consisted of 10 large tensile specimens, as shown in Figure 4, with a 2 inch gauge length and 1 inch width and 10 small tensile specimens like those described earlier. Five of each group were cut longitudinally, that is, in the same direction as rolled and five were cut transversely to the rolling direction. Plate number 8, which was not rolled, was cut in the same manner as the other plates. A 3 square inch plate, a 1/2 inch micro (micro refers to a specimen type used for micro-examination of grain structure), and resistivity specimens were also cut from each of the plates. The resistivity and micro are not shown in the cutting schedule.

The purpose of the small tensile specimens was to determine tensile properties of each of the plates. The larger tensile specimens were to be used for combination tensile and eddy measurements.

Mechanical Analysis of Plates

To mechanically characterize the cold work status of the plates, the small tensile specimens were tested for Young's modulus, yield strength at 0.2% offset, tensile strength, elongation, and percent reduction of area.

Two tensile specimens from each set of five were tested for modulus and yield strength only on the 150,000 pound capacity Materials Testing System. The results of these tests are given in Table VI (see Appendix B). The strain was measured by the use of strain gages for accurate modulus and yield. The tests were run at a constant crosshead speed of .05 in/min. Two other tensile specimens were tested for tensile strength, elongation, and percent reduction in area on the 60,000 pound capacity Tinius Olsen. These tests were run at a constant

Figure 4. The large two inch gage length tensile specimen.

crosshead speed of .15 in/min. until rupture occurred. No strain measuring device was used. The results of these tests are given in Table VII (see Appendix B).

As might be expected in cold working this material, the yield strength and tensile strength increased with cold work, whereas the elongation and percent reduction in area decreased.

Due to anisotropy being induced by cold working, a considerable difference in transverse and longitudinal tensile strength and yield strength were noted. The transverse specimens were noticeably higher in tensile strength and lower in yield strength in most cases. The tensile machines used in these tests were calibrated and certified per ASTM-E4.

Metallographic Analysis of Plates

In order to examine the structural details of the material, a 1/2 X 1/2 inch micro was taken from each of the six plates used in the testing. The micro specimens were mounted and etched. The etched surface examined from each plate was the rolled cross-section in a plane parallel to the rolling direction. Two etches were used on the micros. The result of the etch used to define slip planes is shown in Figure 5, and the result of the etch used to define grain boundaries in Figure 6.

As the amount of cold work increased, the distortion of grains and the number of slip lines increased as can be seen in Figures 5 and 6.

100X

Plate 8-Annealed

100X

Plate 9-10% Cold Work

100X

Plate 10-20% Cold Work

100X

Plate 11-30% Cold Work

100X

Plate 12-40% Cold Work

100X

Plate 13-50% Cold Work

Figure 5. Photomicrographs etched for definition of slip planes.

100X

Plate 8-Annealed

100X

Plate 9-10% Cold Work

100X

Plate 10-20% Cold Work

100X

Plate 11-30% Cold Work

100X

Plate 12-40% Cold Work

100X

Plate 13-50% Cold Work

Figure 6. Photomicrographs etched for definition of grain boundaries.

A micro hardness examination using a diamond pyramid was made on each of the six plates. The diamond pyramid hardness was determined, using a pyramid with an apex angle of 136° under 500 gram load.

In the D.P.H. study, four micros were machined from the remaining material of each plate. Two from each set of micros were mounted and etched on the rolled cross-section whose plane is parallel to the rolling direction. These are identified as longitudinal (L). The other two of each set were mounted and etched in the plane perpendicular to the rolling direction. These are identified as transverse (T). In the case of plate number 13, eight micros were machined and four mounted in each direction.

The hardness study was conducted to determine three things: (1) The difference in hardness from plate to plate, (2) the difference in hardness between transverse and longitudinal sections, and (3) the variation in hardness over the cross-sectional thickness.

Five hardness readings were taken at each mm interval across the thickness of the specimen. The five hardnesses at each level were spread over the 1/2 inch width of the micro.

The average hardness and standard deviation at each level is given in Table VIII (see Appendix B). The analysis of variance was run on the hardness of each specimen to determine if there was significant difference in hardness across the thickness of the specimen.

Those specimens in which there was a significant difference are identified in Table VIII by signifying the two hardest levels in the specimen. The total average hardness for each direction of each plate was determined by averaging all the hardness values of all specimens for a particular plate and direction. These values are given in

Table IX (see Appendix B). A significant difference in hardness over the thickness, as determined by the analysis of variance, was found to be the case on all specimens from plate number 8. The hardest points occurred at or near the surface. In the case of plate number 9, there was a significant difference in hardness for three out of the four specimens, and in these specimens, the hardest points were at the surface. In plate number 10, there was a significant difference in hardness for only one of the four specimens. Plate number 11 had two out of four of the specimens with a significant difference in hardness. The hardest points occurred near the surface in one case and near the center in the other.

There was no significant differences for any of the specimens in plate number 12. Plate number 13 had two specimen out of eight with hardness levels which showed a significant difference.

The results of the hardness tests on the plates show that the significant difference between levels occurs most frequently in plate numbers 8 and 9, and less frequently in plate numbers 10, 11, 12, and 13. In nearly all cases where there is a significant difference, the hardest points occur at or near the surface. These results seem to indicate that the higher percent cold rolling decreases the frequency at which significant differences occur in the various levels and, when these differences do occur, they occur at the surface.

As can be seen in Table IX, there is a difference in hardness for the different directions on the plates which have been rolled. In four out of five plates, the hardest value occurs for the longitudinal direction. As expected, the hardness becomes greater with greater reduction in thickness.

III. INITIAL EDDY CURRENT MEASUREMENTS

Instrumentation

All eddy current measurements were made, using a phase sensitive instrument in the reflection mode. The instrument was a Kervonics modular plug-in unit as shown by simplified diagram in Figure 7 (Reeves, 1972).

The probe used was reflection type as shown in Figure 8 (Dodd and Simpson, 1972). This type probe consists of two detector coils wound in opposite directions and a large driver coil. The driver coil generates the electromagnetic field while the two detector coils measure changes in the field. A simplified diagram of the circuit parameters is shown in Figure 9 (Dodd and Simpson, 1972).

The actual parameters used in Figure 9 are given in Table X (see Appendix B). The parameters of the particular coil used in making the eddy current measurements are given in Table XI (see Appendix B). The meaning of these particular parameters is shown in Figure 1 on page 6.

The parameters used have an effect on the phase shift. Therefore, determining the optimum parameters was accomplished by use of a computer.

The various component instruments, as shown in Figure 7, are as follows: (1) A Model 4200 Krohn-Hite oscillator with frequency range from 10 Hz to 10 MHz and variable amplitude of 3.16 mV to 10V was used. The purpose of the oscillator is to generate the operating frequency for the driver coil. (2) A Kervonics power amplifier module whose function is to supply a higher voltage signal to the driving

Figure 7. Block diagram of the phase sensitive eddy current instrument.

Figure 8. A reflection-type probe near a conductor.

ORNL-DWG 72-671

- V_0 DRIVING VOLTAGE
- R_0 SERIES RESISTANCE IN THE DRIVING CIRCUIT
- C_6 SHUNT CAPACITANCE OF THE DRIVING CIRCUIT
- R_6 D.C. RESISTANCE OF THE DRIVER COIL
- Z_D IMPEDANCE OF THE DRIVER COIL
- M MUTUAL IMPEDANCE BETWEEN THE DRIVER AND PICK-UP COILS
- Z_{PU} IMPEDANCE OF THE PICK-UP COILS
- R_7 D.C. RESISTANCE OF THE PICK UP COILS
- C_7 SHUNT CAPACITANCE OF THE PICK-UP CIRCUIT
- R_8 AMPLIFIER INPUT IMPEDANCE

Figure 9. A simplified circuit diagram for an eddy - current reflection - type probe.

coil was used. (3) A Kervonics F.E.T. three stage high gain video amplifier module, identification number 203, whose purpose is to amplify the signal received from the detector coils, was used. (4) A Kervonics discriminator module identification number 301 was used. The signal from the detector coils is fed into one discriminator, and the signal from the driver coil into another. The pulses from the discriminators which are adjusted to occur when the sinusoidal input signal passes through zero, turn a flip-flop circuit on and off. The integrated output signal is proportional to the phase difference (Dodd, 1968). (5) A Kervonics digital display module, which was also used, contained a digital panel meter on which was displayed the amplified signal from the flip-flop, a sensitivity adjustment from which the amplification of the signal to the panel meter was controlled, and two 50 μ A meters which allowed measurement of the phase of the reflected signal and the voltage amplitude of the power amplifier.

Overall, the maximum sensitivity for the phase sensitive instrument was 0.01 degrees. The phase sensitive instrument was calibrated to read directly in degrees phase shift on the digital panel meter by adjusting the sensitivity on the digital display module after replacing the reflection probe with the RLC phase shift network calibrator. Due to the arrangement of the instrument, the sign of the value taken from the digital panel meter had to be reversed to give the correct phase shift. This was done for all the readings taken during the measurements.

Experimental Considerations

The purpose of this experimentation is to measure the permeability changes in the cold reduced 316 stainless steel. This was done by

measuring phase changes in the material and converting to relative permeability change. The permeability and conductivity contributions to phase change vary with $\omega\mu\sigma r^2$.

In Figure 10, we show the calculated value of phase shift due to a 5% conductivity change versus $\omega\mu\sigma r^2$ for a reflection coil above an infinitely thick conductor. Taking these factors into account, measurement frequencies of 50 kHz and 200 kHz were chosen.

The values of $\omega\mu\sigma r^2$ calculated for 50 kHz and 200 kHz were 1.22 and 4.90, respectively. Using these values in connection with the calculated curves in Figure 10, it was possible to determine the contributions of conductivity at 50 kHz and 200 kHz. The contribution of permeability was determined from a similar chart of phase change due to permeability versus $\omega\mu\sigma r^2$. These contributions are given by the equations:

$$(1) \quad \phi_{50} = \phi_{\mu} + \phi_{\sigma}.$$

and

$$(2) \quad \phi_{200} = .25 \phi_{\mu} + 1.25 \phi_{\sigma}.$$

where ϕ_{50} and ϕ_{200} are the phases measured at 50 kHz and 200 kHz, respectively. The phase contributions for permeability and conductivity at 50 kHz are ϕ_{μ} and ϕ_{σ} , respectively. From equations (1) and (2), it is obvious that the contribution to phase shift due to permeability becomes greatly reduced in going from 50 kHz to 200 kHz. In solving equations (1) and (2), ϕ_{μ} and ϕ_{σ} are determined to be:

$$(3) \quad \phi_{\mu} = 1.25 \phi_{50} - \phi_{200}.$$

Figure 10. Phase shift due to a 5 percent conductivity variation, and percent error due to lift-off versus the $\omega\mu\sigma\bar{r}^2$ value.

$$(4) \quad \phi_{\sigma} = \phi_{200} - 0.25 \phi_{50}.$$

Measurements

Eddy current measurements were made at frequencies of 50 kHz and 200 kHz on each of fifty-nine tensile specimens (a drawing of the type of tensile specimen used is shown in Figure 4 on page 13).

The phase sensitive instrumentation was set up for each frequency after a warm up period of at least two hours. After the instrumentation had been set for a particular frequency, the "zero lift-off" was set for 3 mils on a specimen from plate number 10 and checked for plate number 12. The phase change due to 2 mils lift-off was also checked for plates 10 and 12 and was found to be something less than 0.01 degrees. All measurements on the specimens were kept within the change in amplitude of the reflected signal due to 3 mil lift-off as determined from a 50 μ A meter on the Kervonics digital display module.

All tests were conducted in the temperature range of 24.5°C to 26°C. Each of the specimens tested was selected for test in a random order to eliminate any bias. The specimen was centered over the probe and probe holder. The probe holder supported both probe and specimen and allowed readings to be made without hand contact. The specimen was allowed to remain in contact with the probe for approximately one minute after which three or four readings were made at different points along the gage length of the specimen on that same side. This gave a total of approximately 40 measurements for each plate. This technique of measurement was found to give the most consistent results.

It was necessary to apply a correction to the measurements made at 50 kHz on plates 12 and 13, for which the assumption of infinite thickness was invalid. A correction factor for these particular specimens was determined by placing a second specimen of the same material back of the specimens in question and making the measurement, then removing the backing specimen and remeasuring. The difference between the first and second of these two measurements is the correction factor. An average correction for each plate was determined and added to the average values of the eddy current measurements as shown in Table XII (see Appendix B).

Analysis of Measurements

To make calculations simpler, all the average phase shift values at each frequency were shifted so that the lowest value became zero. In this case, the lowest value was for the minimum cold reduced condition. These values were then used in equations (3) and (4) to determine the contribution to phase shift due to permeability and conductivity at 50 kHz. The results of these calculations are given in Table XIII (see Appendix B).

The phase shift contribution due to permeability and conductivity at 50 kHz are plotted versus the cold reduced condition of the material in Figure 11. In this range, theory confirms that a permeability increase produces a positive phase shift, and that a conductivity increase produces a negative phase shift. The phase shift changes due to permeability given in Table XIII were converted directly into relative permeability change in parts per million, using a graph plotted from values calculated by computer. These values are also given in Table XIII.

Figure 11. Plot of ϕ_{σ} and ϕ_{μ} versus the percent cold reduced state of the large tensile specimens.

The standard deviation for relative permeability and for phase shift due to permeability and conductivity were approximated (Hogg and Craig, 1969) and are given in Table XIV.

Relative permeability change versus the cold reduced state of the material is plotted in Figure 12. One standard deviation bars have been added to each point in Figure 12. Second order least square parabolas have been drawn in Figures 11 and 12 to approximate the curves for each set of points.

IV. FINAL EDDY CURRENT MEASUREMENTS

Elongation of Large Tensile Specimens

Of the fifty-nine original tensile specimens measured by eddy current at 50 kHz and 200 kHz, twenty-seven of the longitudinal cut tensile specimens were successfully stretched to various elongations.

The purpose of elongating these various cold reduced tensile specimens was to determine the effect of this type of straining operation on the permeability of the material using eddy current techniques.

Before tensile pulling the specimens, it was necessary to gage mark each specimen with two inch gage marks on both sides of the specimen. The specimens were pulled on a 120,000 pound capacity, Tinius Olsen Universal testing machine. In order to estimate the amount of elongation which had occurred during the test, the crosshead movement was measured, using a Tinius Olsen deflectometer and recorded versus load on a Tinius Olsen recorder. The recorder and deflectometer were set for a low magnification with two inches crosshead deflection corresponding to ten inches of chart on the recorder.

Figure 12. Plot of permeability versus the percent cold reduced state of the large tensile specimens.

Because not all the deflection in the crosshead is due to elongation within the two inch gage length of the specimen, it was necessary to pull at least two tensiles before an actual correlation between elongation and deflection could be approximated. Once two specimens from the same plate had been pulled, the rest from that same plate could be elongated to the desired amount. Specimens from plates 8, 9, and 10 were pulled to a maximum of about 60% of the total elongation possible before rupture would occur as estimated from Table III (see Appendix B). Specimens from plates 11, 12, and 13 were pulled to an elongation determined by the onset of necking.

In order to keep the testing controlled, the tensile specimens were pulled at a constant crosshead speed and the temperature of the specimen was monitored during the test using a chromel-alumel thermocouple set up with an ice reference junction and a digital voltmeter.

The complete equipment for the straining of the tensile specimens is shown in Figure 13. A close up of the specimen during the pulling operation is shown in Figure 14. Table XV (see Appendix B) gives the results of the elongation measurements.

Figure 15 shows the five specimens from plate number 8 after the elongation operations have been completed. The elongation within two inches for these particular specimens ranges from 11.5% to 43.0%.

Eddy Current Measurements

Eddy current measurements were made at 50 kHz and 200 kHz on the twenty-seven elongated tensile specimens and the thirty transverse

Figure 13. Equipment used in straining large tensile specimens.

Figure 14. Close up of the straining operation on the large tensile specimens.

Figure 15. Results of tensile straining operation on the five annealed 316 stainless steel specimens.

cut specimens using the same equipment as described in Chapter III, Section III, with the exception that the discriminator module with identification number 204 was used in the place of 301.

The technique was also the same, except that:

- (1) All measurements were made within the gage marks of the pulled tensile specimens.
- (2) When necking of a specimen occurred, the measurements were made in the necked vicinity.
- (3) All specimens from one plate were measured before going to another plate.

Table XVI (see Appendix B) shows a composite of the measurements made on the twenty-seven pulled tensiles. Table XVII (see Appendix B) gives these measurements made on the same specimens in Chapter III, Section III. Table XVIII (see Appendix B) gives the results of the measurements made on the thirty transverse tensile specimens, and Table XIX (see Appendix B) gives measurement results for the same specimens measured in Chapter III, Section III. Each of the averages given in Table XVIII and XIX is for a set of five specimens.

Analysis of Measurements

To determine the phase shift due to permeability at 50 kHz for the various tensile strained specimens and from that the change in relative permeability, it was necessary to compare the measurements made in Section IV of Chapter III, with Section III of Chapter III. An approximation of the phase shift, due to tensile straining, was determined by subtracting the difference between the final and initial measurement of like groups in Tables XVIII and XIX (see Appendix B)

from those differences between the final and initial measurement made on each of the tensile strained specimens taken from XVI and XVII (see Appendix B). The results of these calculations are given in Table XX (see Appendix B). Also given in Table XX, are the phase changes due to permeability and conductivity at 50 kHz as calculated, using equations (3) and (4), Chapter III, Section III, and the change in relative permeability as estimated from the phase shift due to permeability. The standard deviation for the phase shifts due to permeability and conductivity were approximated and are given in Table XXI (see Appendix B) as is the standard deviation for the relative permeability measurements.

The relative permeability change versus percent tensile strain was plotted in Figures 16 through 21 for each cold reduced condition of the material.

One standard deviation bars have also been added to each point in Figures 16 through 21. Second order least square parabolas were plotted in all these figures to approximate the curves for each set of points.

Figure 16. Plot of permeability versus the percent elongation of the annealed tensile specimens.

Figure 17. Plot of permeability versus the percent elongation of the 8.9 percent cold reduced tensile specimens.

Figure 13. Plot of permeability versus the percent elongation of the 18.3 percent cold reduced tensile specimens.

Figure 19. Plot of permeability versus the percent elongation of the 30.8 percent cold reduced tensile specimens.

Figure 20. Plot of permeability versus the percent elongation of the 40.3 percent cold reduced tensile specimens.

Figure 21. Plot of permeability versus the percent elongation of the 49.5 percent cold reduced tensile specimens.

CHAPTER IV

DISCUSSION OF ERROR AND RESULTS

I. ERROR ANALYSIS

Mechanical Properties Measurements

The accuracy of the mechanical properties measurements is dependent on the calibration of the equipment. In this case, the limits are established in ASTM-E4. This error can be approximated to be within $\pm 1\%$. The major differences within a series of tests may be related to the variability of the material being tested.

Eddy Current Measurements

The accuracy of the eddy current instrument was ± 0.01 degrees for digital panel meter stability and $\pm 0.5\%$ accuracy in the calibration technique, a lift off error was also estimated to be something less than 0.01 degrees. The major source of error in these measurements appeared to be the variability within the material and the unexplained shifts in the phase readings due possibly to radio frequency noise.

II. DISCUSSION OF RESULTS

Results of the Mechanical Properties

In Tables VI and VII (see Appendix B), it is seen that there is an increase in yield strength and tensile strength with a decrease in elongation of the material as the cold work increases. This is due primarily to work hardening effects aided in part by the carbon content

and in a small part by the transformation of gamma austenite to alpha martensite (Columbier and Hochman, 1968).

Results of the Permeability Measurements

Plastic deformation is known to cause a phase change in the austenitic stainless steels from a paramagnetic face-centered cubic gamma phase to a body-centered cubic ferromagnetic alpha martensite. It is this resulting phase change in varying degrees depending on the chemical composition of the steel which causes a permeability change.

The major interest of this thesis is the effect of cold working on the permeability of the material. From Figure 13 on page 30, it is seen to increase approximately 400 ppm over a cold reduction to 50%. For the equivalent amount of cold work in percent tensile elongation, the permeability can be approximated from Figure 16 on page 37, to increase by 120 ppm. From these two forms of cold work, the reduction process shows over three times as much change in permeability.

In cold working by rolling, the compression and shearing forces occur on the surface of the material where the measurements are made. A hardness study tabulated in Table VIII (see Appendix B) was conducted across the thickness of the plates to determine significant differences and therefore show the most worked regions.

In a majority of cases where differences did occur, the hardest values were at or near the surface; however, this hardness study was not as complete as it could have been in that, on the average, the hardness measurements began and ended 3 mils from the surface. It was shown by Reeves (1972) on this same cold rolled material that most

of the cold work was within 2 to 6 mils from the surface. In Reeves' research, polishing of the surface resulted in a large decrease in permeability.

Tensile elongation of the various cold reduced states gave very little change in permeability for the annealed and 10% specimens as shown in Figure 16 on page 37, and Figure 17 on page 38. The first large increase occurred in the 20% reduced state for an elongation of 26.5%. This change is shown in Figure 18 on page 39, to be 870 ppm. Starting with the 30% cold reduced specimens, the permeability increase became much larger for small increases in elongation. This increase accelerated for the 40% and 50% cold reduced tensile specimens, as can be seen in Figures 20 through 21 on pages 41 through 42. The largest permeability increases for a particular cold reduced state occurred when the specimen necked due to the greater plastic deformation occurring in the localized necked region.

This acceleration of permeability change with tensile elongation at the greater cold reduced states can best be explained by the introduction of an intermediate phase epsilon between the gamma and alpha phase which is hexagonal close-packed and paramagnetic. This intermediate phase was first described by Cina (1954) and later thoroughly analyzed by Thomas and Mangonon (1970). Cina (1954) found that epsilon became a maximum after a certain amount of plastic deformation and then decreased while the alpha phase increased. Cina believed the alpha phase nucleated from the epsilon phase. Thomas and Mangonon (1970) confirmed this.

The results of this research seem to indicate that the epsilon phase has formed heavily, particularly on the surface of the greater cold reduced specimens, thus allowing nucleation and growth of large amounts of the ferromagnetic alpha martensite with small amounts of tensile elongation on the 30%, 40%, and 50% reduced tensile specimens.

Results of Conductivity Phase Change Measurements

Though conductivity measurements are not the subject of this study, it is worth mentioning that phase shift due to conductivity change was the major contribution to the eddy current measurements until the elongated 30%, 40%, and 50% cold reduced specimens were measured.

CHAPTER V

CONCLUSIONS

The following major conclusions were drawn from this research:

1. In cold working by rolling, most of the cold work occurs in the surface.
2. Cold working the specimens by tensile elongation produces a more uniform cold work within the gage length of the specimen.
3. Small amounts of cold working by elongation accelerate the increase in permeability in the greater cold reduced specimens, probably because of the presence of large amounts of an intermediate phase epsilon from which alpha martensite forms.
4. The phase sensitive eddy current technique has been shown to be successful as a nondestructive testing method of determining the conductivity and permeability changes in 316 stainless steel and can see predictable differences in cold worked conditions though the method of cold work, the amount of cold work, and the chemical composition of the material will result in variations in the differences.

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APPENDIX A

LIST OF SYMBOLS

In the first column, the symbol used is given; and in the second column, the name is given. In the third and last column, the meter-kilogram-second (MKS) units are given.

<u>Symbol</u>	<u>Name</u>	<u>MKS Units</u>
H	magnetic intensity	$\frac{\text{ampere}}{\text{meter}}$
J	current density	$\frac{\text{coulombs}}{\text{second-meter}^2}$
D	electric displacement	$\frac{\text{coulomb}}{\text{meter}^2}$
E	electric field intensity	$\frac{\text{volt}}{\text{meter}}$
B	magnetic induction	$\frac{\text{weber}}{\text{meter}^2}$
I	applied current	ampere
V	voltage	volt
ϵ	permittivity	$\frac{\text{farad}}{\text{meter}}$
μ	permeability	$\frac{\text{henry}}{\text{meter}}$
σ	conductivity	$\frac{\text{mho}}{\text{meter}}$
j	square root of minus one	
α	separation constant	meter^{-1}
ω	angular frequency	$\frac{\text{radians}}{\text{second}}$

<u>Symbol</u>	<u>Name</u>	<u>MKS Units</u>
α_i	$(\alpha^2 - \omega^2 \mu_i \epsilon_i + j\omega \mu_i \sigma_i)^{1/2}$	meter ⁻¹
β_i	$\frac{\mu_o}{\mu_i} (\alpha^2 - \omega^2 \mu_i \epsilon_i + j\omega \mu_i \sigma_i)^{1/2}$	meter ⁻¹
$J(r_2, r_1)$	$\alpha^2 \int_{r_1}^{r_2} r_o J_1(\alpha r_o) dr_o$	
c	clad thickness	meter
r_1	driver coil inner radius	meter
r_2	driver coil outer radius	meter
$\bar{r}$	mean driver coil radius	meter
r_3	pick-up coil inner radius	meter
r_4	pick-up coil outer radius	meter
L_2	length of driver	meter
L_6	length of pick-up	meter
L_5	pick-up recessed	meter
n	number of turns on driver coil	turn
n'	number of turns on each pick-up coil	turn
L	inductance	henry

APPENDIX B

TABLES

All Tables referred to in this Thesis are contained in Appendix

B.

TABLE I
CHEMICAL ANALYSIS OF 316
STAINLESS STEEL

Elements ^a	Specified Limits	Vendor's Analysis	Y-12 Analysis
Carbon	0.04 - 0.06	0.047	0.0645
Manganese	1.00 - 2.00	1.67	1.73
Phosphorous	0.03 maximum	0.025	0.029
Sulphur	0.03 maximum	0.017	0.016
Silicon	0.75 maximum	0.41	0.386
Chromium	16 - 18	17.40	17.62
Nickel	12 - 14	12.50	12.01
Molybdenum	2 - 3	2.65	2.715
Copper	0.20 maximum	0.15	0.0573
Cobalt	0.10 maximum	b	0.1000
Nitrogen	0.02 - 0.03	b	0.045
Boron	0.001 maximum	b	b
Iron	Balance	b	b

^aElements given in percent by weight.

^bElement Analysis is not given.

TABLE II
Y-12 MECHANICAL PROPERTIES ON
316 STAINLESS STEEL

Mechanical Properties	Y-12 Results	Standard Deviation	Direction ^a
Tensile Strength (psi)	83,730	457	L
	83,360	262	T
Yield Strength ^b (psi)	37,410	312	L
	37,800	190	T
Young's Modulus (psi)	28.5 X10 ⁶	0.37 X10 ⁶	L
	28.4 X10 ⁶	0.05 X10 ⁶	T
Percent Reduction in Area	67.0	2.65	L
	63.7	1.53	T
Percent Elongation	68.3	1.53	L
	64.7	0.53	T
Rockwell B Hardness	79.3	1.72	A

^aL = Taken along thirty inch length.
T = Perpendicular to L direction.
A = No direction.

^bYield Strength was determined using the 0.2% offset method.

TABLE III
VENDOR MECHANICAL PROPERTIES ON
316 STAINLESS STEEL

Tensile Strength (psi)	Yield ^a Strength (psi)	Percent Elongation	Percent Reduction in area	Hardness Rockwell B
82,581	37,097	62	71	75 - 77

^aYield Strength was determined using the 0.2 percent offset method.

TABLE IV
MICROHARDNESS ON AS RECEIVED
316 STAINLESS STEEL

Plate Number	Diamond Pyramid ^a Hardness (Mean)	Conversion to Rockwell B
8	150	78.5
10	153	79.0
12	159	81.0

^aThe load applied was 1 Kg. and the values given are the means.

TABLE V
THE FINAL AND INITIAL REDUCTION
IN THICKNESS MEASUREMENTS ON
THE 316 STAINLESS STEEL

Plate Number	Initial Thickness (in)	Standard Deviation	Final Thickness (in)	Standard Deviation	Percent Reduction in Thickness
8	0.3316	0.00096	a	a	0
9	0.3354	0.00209	0.3054	0.00084	8.9
10	0.3415	0.00346	0.2791	0.00203	18.3
11	0.3459	0.00099	0.2394	0.00113	30.8
12	0.3457	0.00223	0.2062	0.00107	40.3
13	0.3388	0.00252	0.1711	0.00127	49.5

^aThis plate was not rolled; therefore, there was no change in the thickness.

TABLE VI
MECHANICAL PROPERTIES DETERMINED USING
MATERIALS TESTING SYSTEM

Plate ^a Number	Yield Strength ^b (psi)	Standard Deviation	Young's Modulus (x10 ⁶ psi)	Standard Deviation
8L	35,750	59	29.2	1.20
8T	35,150	529	29.5	0.85
9L	68,040	155	27.5	0.0
9T	75,050	1060	28.4	0.35
10L	93,530	161	26.8	0.78
10T	95,750	526	28.0	0.0
11L	121,200	40	26.9	0.14
11T	117,790	670	28.0	0.64
12L	135,790	190	26.5	0.14
12T	126,990	1240	29.0	0.14
13L	142,800	1920	25.4	0.0
13T	137,300	750	28.6	0.42

TABLE VI (Continued)

^aL = In the same direction as rolled or as in the case of plate number 8 along the 30 inch length.

T = Perpendicular to L direction.

^bYield Strength was determined by the 0.2 percent offset method.

TABLE VII
MECHANICAL PROPERTIES DETERMINED USING
TINIUS OLSEN SYSTEM

Plate ^a Number	Tensile Strength (psi)	Standard Deviation	Percent Reduction in Area	Standard Deviation	Percent Elongation in 1 inch	Standard Deviation
8L	84,710	552	71.4	0.42	69.2	2.47
8T	84,970	551	65.6	1.77	66.5	2.12
9L	93,740	337	69.7	0.0	57.0	2.12
9T	94,640	2,087	61.2	0.21	51.0	1.41
10L	110,200	300	64.8	0.78	36.5	0.71
10T	111,500	290	58.2	1.06	34.5	0.0
11L	135,200	960	56.1	1.70	23.0	b
11T	139,300	600	45.6	4.52	20.5	0.71
12L	147,900	660	54.0	3.04	19.2	0.35
12T	154,600	600	39.0	2.76	15.2	0.35
13L	157,900	90	51.0	0.71	16.0	0.0
13T	168,200	340	38.6	0.28	13.0	0.0

TABLE VII (Continued)

^aL = In the same direction as rolled or as in the case of plate number 8 along the 30 inch length.

T = Perpendicular to L direction.

^bOnly one value was obtained for elongation.

TABLE VIII

AVERAGE DIAMOND PYRAMID HARDNESS AT ONE MM
INTERVALS ACROSS PLATE THICKNESS

Plate Number	Direction ^a and Specimen Number	Hardness ^b	Standard Deviation
8	L-1	164.9 ^c	9.34
		157.4	4.22
		155.7	4.82
		153.1	5.40
		143.6	3.44
		153.8	4.55
		153.6	2.31
		154.2	3.63
		163.8	5.99
		166.9 ^c	3.86
8	L-2	174.0 ^c	23.48
		155.1	3.61
		150.9	4.98
		147.5	3.66
		144.7	5.03
		146.6	4.85
		150.2	5.70
		156.9	4.08
		159.4 ^c	5.06
8	T-1	165.0 ^c	8.25
		157.2	6.69
		151.9	10.24
		147.0	5.58
		149.9	7.38
		148.6	3.66
		147.1	5.06
		151.7	4.68
		164.1 ^c	11.74

TABLE VIII (Continued)

Plate Number	Direction ^a and Specimen Number	Hardness ^b	Standard Deviation
8	T-2	161.3	8.80
		163.2 ^c	4.07
		155.3	7.47
		149.8	6.07
		154.9	6.43
		152.3	4.42
		154.2	5.03
		156.1	3.64
		164.3 ^c	4.68
		158.7	3.11
9	L-1	218.1	9.50
		225.1	4.98
		225.3	3.16
		215.4	8.26
		216.2	3.78
		226.2	5.86
		230.5	7.66
		227.2	5.58
		227.8	24.51
9	L-2	229.9 ^c	15.41
		234.6 ^c	5.64
		228.5	10.24
		224.8	4.85
		218.6	7.66
		220.5	4.59
		222.3	6.35
		223.0	1.48
		219.7	5.38
9	T-1	236.6 ^c	2.10
		232.2	9.20
		221.8	5.17
		213.3	3.97
		215.5	5.26
		217.2	9.54
		224.5	8.70
		231.5	11.22
		235.7 ^c	13.51

TABLE VIII (Continued)

Plate Number	Direction ^a and Specimen Number	Hardness ^b	Standard Deviation
9	T-2	237.2 ^c	8.30
		231.3	7.50
		227.9	9.57
		223.3	11.70
		217.7	11.41
		218.3	6.49
		228.8	5.15
		229.6	4.35
		242.3 ^c	19.45
10	L-1	296.8	8.30
		307.3	5.35
		309.9	12.45
		304.2	12.01
		307.8	7.98
		307.7	14.73
		309.1	15.85
		297.7	6.08
10	L-2	282.5	14.92
		282.2	7.86
		286.5	10.79
		288.4	13.88
		292.1	18.60
		304.1 ^c	8.84
		303.7	18.11
		307.5 ^c	12.47
10	T-1	289.4	7.07
		292.0	12.81
		289.6	11.43
		278.9	11.97
		285.3	7.14
		286.8	6.82
		298.0	20.30
		282.7	6.53

TABLE VIII (Continued)

Plate Number	Direction ^a and Specimen Number	Hardness ^b	Standard Deviation
10	T-2	273.3	13.19
		286.6	10.72
		280.5	14.24
		275.5	14.95
		267.4	17.18
		272.9	22.71
		268.3	19.62
		268.3	20.66
11	L-1	335.2	11.85
		337.5	7.37
		325.9	12.19
		322.0	15.10
		348.6	22.97
		329.1	12.16
		337.1	19.94
11	L-2	340.1	13.47
		353.8	15.14
		349.4 ^c	9.82
		330.8	7.91
		357.6 ^c	11.62
		343.2	4.14
		323.0	7.12
11	T-1	337.7	13.37
		325.9	18.85
		330.9	24.14
		339.1	26.08
		338.0	10.06
		344.0	13.42
		347.3	10.15

TABLE VIII (Continued)

Plate Number	Direction ^a and Specimen Number	Hardness ^b	Standard Deviation
11	T-2	345.2 ^c	18.24
		339.5	10.94
		308.9	12.10
		333.9	14.11
		322.9	13.80
		347.7 ^c	16.68
		331.9	19.77
12	L-1	337.4	17.20
		346.7	10.00
		350.4	9.76
		349.1	22.80
		340.7	15.36
		356.2	15.15
12	L-2	344.4	11.73
		352.3	7.71
		345.0	12.80
		343.3	8.04
		346.1	15.04
		353.6	28.14
12	T-1	347.9	10.48
		346.4	10.87
		340.9	10.30
		343.5	13.76
		339.7	15.92
		343.5	21.44
12	T-2	353.9	7.97
		347.4	11.17
		342.2	17.81
		347.9	20.72
		348.1	23.73
		350.1	15.91
13	L-1	361.8	11.08
		377.3	21.77
		369.6	15.16
		370.0	5.56
		367.8	12.10

TABLE VIII (Continued)

Plate Number	Direction ^a and Specimen Number	Hardness ^b	Standard Deviation
13	L-2	370.0	10.31
		384.6	19.35
		389.7	15.76
		377.6	18.53
		373.0	24.89
13	L-3	341.9	9.87
		357.2	12.59
		368.6	16.78
		379.4 ^c	20.66
		373.3 ^c	10.26
13	L-4	368.6	16.58
		379.5	10.97
		366.6	20.31
		356.5	19.58
		359.7	10.86
13	T-1	365.8	16.49
		353.5	20.49
		345.7	17.09
		330.9	24.71
		331.8	18.66
13	T-2	385.0 ^c	16.63
		371.4 ^c	16.50
		361.4	13.20
		323.1	8.41
		337.8	16.44
13	T-3	342.8	23.80
		357.7	11.66
		354.5	10.07
		355.6	12.47
		362.0	14.00
13	T-4	353.0	12.78
		370.2	16.33
		357.3	14.51
		345.0	21.16
		360.2	19.63

TABLE VIII (Continued)

^aL = Cross section whose plane is parallel to the rolling direction.

T = Cross section whose plane is perpendicular to the rolling direction.

^bThe hardness was taken with an apex angle of 136° under a 500 gm. load.

^cA significant difference was determined across the thickness of the specimen, and these are the two hardest points.

TABLE IX
TOTAL AVERAGE DIAMOND PYRAMID HARDNESS
FOR THE DIRECTION OF EACH PLATE
OF 316 STAINLESS STEEL

Plate Number	Direction ^a	Hardness ^b	Standard Deviation	Number of Hardness Values
8	L	155.5	9.79	94
8	T	155.4	8.30	95
9	L	224.1	9.66	90
9	T	226.7	11.76	88
10	L	299.2	14.75	80
10	T	281.0	15.93	80
11	L	336.3	15.56	70
11	T	335.2	18.19	70
12	L	347.1	15.53	60
12	T	346.0	14.77	60
13	L	369.7	17.83	100
13	T	353.2	21.17	100

^aL = Cross section whose plane is parallel to the rolling direction.

T = Cross section whose plane is perpendicular to the rolling direction.

^bThe hardness was taken with an apex angle of 136° under 500 gm. load.

TABLE X
CIRCUIT PARAMETERS USED IN EDDY
CURRENT MEASUREMENTS

Parameters	Value
Driver Resistance	53.12 ohms
Driver Inductance	0.222 millihenries
Number of Driver Turns	252
Driver Shunt Capacitance	1×10^{-9} farads
Pick-up Resistance	1344.2 ohms
Pick-up Inductance	0.565 millihenries
Number of Pick-up Turns	598
Pick-up Shunt Capacitance	1×10^{-9} farads
Driver Series Resistance (50kHz)	2000 ohms
Pick-up Shunt Resistance (50KHz)	1×10^6 ohms
Driver Series Resistance (50kHz)	5000 ohms
Pick-up Shunt Resistance (200KHz)	1×10^6 ohms

TABLE XI
EDDY CURRENT PROBE PARAMETERS

Parameter	Description	Value ^a
R_1	Inner Radius of Driver	0.750
R_2	Outer Radius of Driver	1.250
R_3	Inner Radius of Pickup	0.350
R_4	Outer Radius of Pickup	0.700
L_2	Length of Driver	0.300
L_6	Length of Pickup	0.100
L_5	Pickup Recessed	0

^aThese values have been determined by dividing each dimension by the mean coil radius which is 0.060 inches in this case.

TABLE XII
INITIAL EDDY CURRENT MEASUREMENTS
ON THE 316 STAINLESS STEEL

Plate Number	Frequency (kHz)	Phase Shift (degrees)	Standard Deviation	Number of Readings
8	50	0.131	0.0284	40
9	50	0.179	0.0149	40
10	50	0.221	0.0189	40
11	50	0.296	0.0133	36
12	50	0.356 ^a	0.0168	40
13	50	0.408 ^b	0.0144	40
8	200	0.163	0.0229	40
9	200	0.217	0.0149	40
10	200	0.255	0.0200	40
11	200	0.346	0.0141	33
12	200	0.383	0.0128	37
13	200	0.420	0.0144	40

^aThis value has been corrected for thickness by adding 0.01 degrees.

^bThis value has been corrected for thickness by adding 0.03 degrees.

TABLE XIII
CALCULATED VALUES OF PERMEABILITY
AND CONDUCTIVITY

Percent Reduction in Thickness	ϕ_{50}^a Phase Shift (degrees)	ϕ_{200}^b Phase Shift (degrees)	ϕ_{μ}^c Phase Shift (degrees)	ϕ_{σ}^d Phase Shift (degrees)	Relative Permeability Change (ppm)
0	0.0	0.0	0.0	0.0	0
8.9	0.048	0.054	0.006	0.042	26
18.3	0.090	0.092	0.020	0.070	87
30.8	0.165	0.183	0.023	0.142	100
40.3	0.225	0.220	0.061	0.164	266
49.5	0.277	0.257	0.089	0.188	388

^a ϕ_{50} Represents the phase shift as measured at 50 kHz.

^b ϕ_{200} Represents the phase shift as measured at 200 kHz.

^c ϕ_{μ} Represents the phase shift due to permeability at 50 kHz.

TABLE XIII (Continued)

ϕ_{σ}^d Represents the phase shift due to conductivity at 50 kHz.

TABLE XIV
ESTIMATED VALUES OF STANDARD DEVIATION FOR PERMEABILITY
AND CONDUCTIVITY PHASE SHIFT

Percent Reduction in Thickness	V_{50}^a Variance (degrees ²)	V_{200}^b Variance (degrees ²)	S_{μ}^c Standard Deviation (degrees)	S_{σ}^d Standard Deviation (degrees)	Relative Permeability Standard Deviation (ppm)
0	0.000307	0.000524	0.0222	0.0178	97
8.9	0.000222	0.000222	0.0091	0.0118	40
18.3	0.000357	0.000400	0.0102	0.0159	40
30.8	0.000177	0.000199	0.0072	0.0112	31
40.3	0.000282	0.000164	0.0136	0.0099	59
49.5	0.000207	0.000207	0.0088	0.0114	38

$^aV_{50}$ Represents the variance as estimated from the measurements taken at 50 kHz.

$^bV_{200}$ Represents the variance as estimated from the measurements taken at 200 kHz.

$^cS_{\mu}$ Represents the standard deviation as estimated for the permeability phase shift.

TABLE XIV (Continued)

$d_{S_{\sigma}}$ Represents the standard deviation as estimated for the conductivity phase shift.

TABLE XV
RESULTS OF STRAINING OPERATION ON
LARGE TENSILE SPECIMENS

Specimen Number	Percent Elongation in 2 inches	Crosshead Speed (in/min)	Approx. Temperature Change During Test (°C)
8L-1	11.5	0.038	2
2	14.0	0.038	2
3	27.5	0.038	3
4	43.0	0.038	5
5	21.5	0.038	2
9L-1	11.5	0.038	5
2	19.0	0.038	4
3	25.0	0.038	6
4	31.0	0.038	4
5	34.0	0.038	5
10L-1	12.0	0.022	2
2	14.0	0.022	5
3	6.0	0.022	2
5	25.5	0.022	4
11L-1	4.0	0.016	3
3 ^a	10.0	0.016	4
4 ^b	13.5	0.016	4
5	7.5	0.016	2
12L-1	3.5	0.022	4
2 ^a	7.5	0.006	2
3 ^b	5.5	0.006	2
4 ^b	11.0	0.006	2
5	2.5	0.006	1
13L-1	2.5	0.038	2
2	4.5	0.022	4
3 ^a	7.5	0.022	3
4	0	0.022	0

^aSlight necking occurred in these specimens.

^bNecking occurred in these specimens.

TABLE XVI
FINAL EDDY CURRENT MEASUREMENTS MADE ON
THE LONGITUDINAL TENSILE SPECIMENS

Specimen Number	Frequency (kHz)	Phase Shift (-1X degrees)	Standard Deviation (degrees)	Number of Readings
8L-1	200	0.706	0.0160	4
	50	0.920	0.0000	5
2	200	0.700	0.0163	4
	50	0.902	0.0239	5
3	200	0.675	0.0141	6
	50	0.875	0.0229	5
4	200	0.634	0.0197	4
	50	0.851	0.0167	5
5	200	0.671	0.0240	6
	50	0.916	0.0114	5
9L-1	200	0.662	0.0096	4
	50	0.880	0.0082	4
2	200	0.656	0.0125	4
	50	0.861	0.0085	4
3	200	0.625	0.0178	4
	50	0.844	0.0114	5
4	200	0.604	0.0111	4
	50	0.811	0.0080	8
5	200	0.599	0.0160	5
	50	0.780	0.0167	6
10L-1	200	0.877	0.0234	5
	50	0.818	0.0204	6
2	200	0.855	0.0122	5
	50	0.808	0.0110	5
3	200	0.933	0.0135	5
	50	0.859	0.0193	4
5	200	0.717	0.0335	7
	50	0.550	0.0381	5

TABLE XVI (Continued)

Specimen Number	Frequency (kHz)	Phase Shift (-1X degrees)	Standard Deviation (degrees)	Number of Readings
11L-1	200	0.810	0.0106	5
	50	0.738	0.0192	5
3	200	0.739 ^a	0.0035	4
	50	0.547 ^a	0.0153	3
4	200	0.672 ^b	0.0179	5
	50	0.457 ^b	0.0208	3
5	200	0.796	0.0167	5
	50	0.676	0.0477	5
12L-1	200	0.774	0.0108	5
	50	0.684	0.0344	5
2	200	0.654 ^a	0.0149	4
	50	0.450 ^a	0.0346	3
3	200	0.745	0.0143	5
	50	0.614 ^b	0.0358	5
4	200	0.545 ^b	0.0192	4
	50	0.143 ^b	0.0289	3
5	200	0.767	0.0098	5
	50	0.690	0.0141	5
13L-1	200	0.735	0.0087	5
	50	0.636	0.0114	5
2	200	0.717	0.0152	3
	50	0.550 ^b	0.0158	5
3	200	0.432 ^b	0.0340	3
	50	-0.397 ^b	0.270	3
4	200	0.754	0.0129	5
	50	0.674	0.0114	5

^aSlight necking occurred in these specimens and the measurements were made in the region of the necking.

^bNecking occurred in these specimens and the measurements were made within this necked portion of the specimen.

TABLE XVII
INITIAL EDDY CURRENT MEASUREMENTS MADE ON
THE LONGITUDINAL TENSILE SPECIMENS

Specimen Number	Frequency (kHz)	Phase Shift (degrees)	Standard Deviation (degrees)	Number of Readings
8L-1	200	0.188	0.0050	4
	50	0.155	0.0252	4
2	200	0.169	0.0132	4
	50	0.138	0.0150	4
3	200	0.146	0.0095	4
	50	0.135	0.0191	4
4	200	0.152	0.0171	4
	50	0.122	0.0126	4
5	200	0.152	0.0171	4
	50	0.128	0.0222	4
9L-1	200	0.205	0.0129	4
	50	0.170	0.0216	4
2	200	0.194	0.0075	4
	50	0.170	0.0082	4
3	200	0.199	0.0025	4
	50	0.178	0.0150	4
4	200	0.224	0.0075	4
	50	0.170	0.0141	4
5	200	0.228	0.0050	4
	50	0.185	0.0058	4
10L-1	200	0.242	0.0065	4
	50	0.218	0.0222	4
2	200	0.238	0.0465	4
	50	0.222	0.0419	4
3	200	0.246	0.0189	4
	50	0.222	0.0222	4
5	200	0.260	0.0082	4
	50	0.222	0.0096	4

TABLE XVII (Continued)

Specimen Number	Frequency (kHz)	Phase Shift (degrees)	Deviation (degrees)	Number of Readings
11L-1	200	0.350	0.0183	4
	50	0.290	0.0082	4
3	200	0.340	0.0173	3
	50	0.295	0.0058	4
4	200	0.345	0.0180	3
	50	0.300	0.0082	4
5	200	0.333	0.0176	3
	50	0.297	0.0115	3
12L-1	200	0.392	0.0171	4
	50	0.348	0.0126	4
2	200	0.375	0.0087	3
	50	0.335	0.0129	4
3	200	0.393	0.0058	3
	50	0.342	0.0189	4
4	200	0.392	0.0155	4
	50	0.352	0.0126	4
5	200	0.380	0.0087	3
	50	0.365	0.0238	4
13L-1	200	0.419	0.0025	4
	50	0.365	0.0100	4
2	200	0.414	0.0125	4
	50	0.362	0.0096	4
3	200	0.424	0.0229	4
	50	0.375	0.0058	4
4	200	0.414	0.0095	4
	50	0.402	0.0150	4

TABLE XVIII
FINAL EDDY CURRENT MEASUREMENTS MADE ON
THE TRANSVERSE TENSILE SPECIMENS

Specimen Number	Frequency (kHz)	Phase Shift ^a (-1X degrees)	Standard Deviation (degrees)	Number of Readings
8T	200	0.736	0.0211	21
	50	0.945	0.0124	26
9T	200	0.680	0.0165	20
	50	0.895	0.0123	20
10T	200	0.957	0.0126	24
	50	0.902	0.0087	20
11T	200	0.835	0.0136	25
	50	0.762	0.0324	30
12T	200	0.788	0.0173	25
	50	0.736	0.0236	27
13T	200	0.747	0.0119	25
	50	0.681	0.0150	25

^aEach value represents an average of measurements taken on five specimens.

TABLE XIX
INITIAL EDDY CURRENT MEASUREMENTS MADE
ON THE TRANSVERSE TENSILE SPECIMENS

Specimen Number	Frequency (kHz)	Phase Shift ^a (degrees)	Standard Deviation (degrees)	Number of Readings
8T	200	0.164	0.0264	20
	50	0.131	0.0238	20
9T	200	0.225	0.0096	20
	50	0.183	0.0149	20
10T	200	0.258	0.0147	20
	50	0.220	0.0159	20
11T	200	0.348	0.0121	20
	50	0.296	0.0164	20
12T	200	0.379	0.0111	20
	50	0.344	0.0153	20
13T	200	0.421	0.0160	20
	50	0.378	0.0106	20

^aEach value represents an average of measurements taken on five specimens.

TABLE XX
CALCULATED CHANGES IN PERMEABILITY AND CONDUCTIVITY
FOR LONGITUDINAL TENSILE SPECIMENS

Specimen Number	$\Delta\phi_{50}^a$ Phase Shift (degrees)	$\Delta\phi_{200}^b$ Phase Shift (degrees)	$\Delta\phi_{\mu}^c$ Phase Shift (degrees)	$\Delta\phi_{\sigma}^d$ Phase Shift (degrees)	Relative Permeability Change (ppm)
8L-1	0.001	0.006	-0.005	0.0006	-22
2	0.036	0.031	0.014	0.022	61
3	0.066	0.079	0.004	0.062	17
4	0.103	0.114	0.015	0.088	65
5	0.032	0.077	-0.037	0.069	-161
9L-1	0.028	0.033	-0.003	0.031	13
2	0.047	0.055	0.004	0.043	17
3	0.056	0.081	-0.011	0.067	-48
4	0.097	0.077	0.044	0.053	192
5	0.133	0.078	0.063	0.050	275
10L-1	0.086	0.096	0.012	0.074	52
2	0.092	0.122	-0.007	0.099	-31
3	0.041	0.036	0.015	0.026	65
5	0.350	0.238	0.200	0.150	872
11L-1	0.030	0.023	0.014	0.016	61
3	0.215	0.104	0.166	0.050	724
4	0.301	0.166	0.210	0.091	916
5	0.085	0.054	0.052	0.033	227

TABLE XX (Continued)

Specimen Number	$\Delta\phi_{50}^a$ Phase Shift (degrees)	$\Delta\phi_{200}^b$ Phase Shift (degrees)	$\Delta\phi_{\mu}^c$ Phase Shift (degrees)	$\Delta\phi_{\sigma}^d$ Phase Shift (degrees)	Relative Permeability Change (ppm)
12L-1	0.048	0.001	0.059	-0.011	257
2	0.295	0.138	0.231	0.064	1007
3	0.124	0.029	0.126	-0.002	549
4	0.535	0.230	0.501	0.084	2184
5	0.025	0.020	0.011	0.014	48
13L-1	0.058	0.014	0.058	0.000	253
2	0.147	0.037	0.147	0.000	641
3	1.081	0.312	1.039	0.042	4530
4	-0.017	0.000	-0.021	0.004	-92

^a $\Delta\phi_{50}$ Represents the change in phase shift due to tensile straining as measured at 50 kHz.

^b $\Delta\phi_{200}$ Represents the change in phase shift due to tensile straining as measured at 200 kHz.

^c $\Delta\phi_{\mu}$ Represents the calculated change in permeability phase shift due to tensile straining.

^d $\Delta\phi_{\sigma}$ Represents the calculated change in conductivity phase shift due to tensile straining.

Table XXI

ESTIMATED STANDARD DEVIATION VALUES FOR PERMEABILITY AND CONDUCTIVITY

PHASE SHIFT FOR THE LONGITUDINAL TENSILE SPECIMENS

Specimen Number	V_{50}^a Variance (degrees ²)	V_{200}^b Variance (degree ²)	S_{μ}^c Standard Deviation (degrees)	S_{σ}^d Standard Deviation (degrees)	Relative Permeability Standard Deviation (ppm)
8L-1	0.0014	0.0014	0.023	0.030	100
2	0.0015	0.0016	0.022	0.032	96
3	0.0016	0.0014	0.027	0.029	118
4	0.0012	0.0018	0.007	0.034	30
5	0.0014	0.0020	0.011	0.035	48
9L-1	0.0009	0.00062	0.023	0.019	100
2	0.00053	0.00058	0.013	0.019	57
3	0.00073	0.00058	0.018	0.020	78
4	0.00062	0.00053	0.017	0.018	74
5	0.00068	0.00062	0.017	0.020	74
10L-1	0.0012	0.00096	0.025	0.024	109
2	0.0022	0.0027	0.022	0.041	96
3	0.0012	0.00090	0.025	0.023	109
5	0.0018	0.0016	0.028	0.031	122
11L-1	0.0018	0.00078	0.037	0.021	161
3	0.0016	0.00068	0.035	0.020	153
4	0.0018	0.00096	0.035	0.024	153
5	0.0037	0.00090	0.057	0.021	249

TABLE XXI (Continued)

Specimen Number	V_{50}^a Variance (degrees ²)	V_{200}^b Variance (degrees ²)	S_{μ}^c Standard Deviation (degrees)	S_{σ}^d Standard Deviation (degrees)	Relative Permeability Standard Deviation (ppm)
12L-1	0.0021	0.00084	0.040	0.022	174
2	0.0021	0.00073	0.041	0.02	179
3	0.0024	0.00058	0.045	0.019	196
4	0.0018	0.0010	0.035	0.024	153
5	0.0015	0.00058	0.035	0.018	153
13L-1	0.00058	0.00048	0.017	0.017	74
2	0.00068	0.00032	0.013	0.023	57
3	0.0734	0.0021	0.271	0.000	1182
4	0.00068	0.00068	0.016	0.021	70

$^aV_{50}$ Represents the variance as estimated from the measurements taken at 50 kHz.

$^bV_{200}$ Represents the variance as estimated from measurements taken at 200 kHz.

$^cS_{\mu}$ Represents the standard deviation as estimated for the permeability phase shift.

$^dS_{\sigma}$ Represents the standard deviation as estimated for the conductivity phase shift.

VITA

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He graduated from Lewis County High School in 1962. The following September he entered the University of Tennessee, from which he graduated with a Bachelor of Science degree in Nuclear Engineering in August, 1966. He has been employed by the Union Carbide Corporation - Nuclear Division, in Oak Ridge, Tennessee, since June, 1967. He is currently a Physicist in charge of the production Mechanical and Physical Properties Laboratory for the Y-12 Plant. He is a member of Sigma Pi Sigma, the American Society for Metals, and the Society for Experimental Stress Analysis.

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