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ABSTRACT

As one in the series of classroom training handbooks, prepared by the U.S. space program, instructional material is presented in this volume concerning familiarization and orientation on eddy current testing. The subject is presented under the following headings: Introduction, Eddy Current Principles, Eddy Current Equipment, Eddy Current Methods, Eddy Current Method Control and Test System Development, Special Applications, and Comparison and Selection of Nondestructive Testing Processes. High product quality and reliability in metal processing are the main concerns throughout the volume. The material is designed for use in the classroom and has practical exercise portions. Successful completion of the corresponding programmed instruction handbook is the prerequisite for receiving classroom training. Included are illustrations for explanation purposes. (CC)

January 1, 1967

QUALITY AND RELIABILITY ASSURANCE LABORATORY

EDDY CURRENT TESTING

RQA/M1-5330.17

GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Form 1262 (September 1961)

PREFACE

Classroom Training Handbook - Eddy Current Testing (5330.17) is one of a series of training handbooks designed for use in the classroom and practical exercise portions of Nondestructive Testing. It is intended that this handbook be used in the instruction of those persons who have successfully completed Programmed Instruction Handbook - Eddy Current Testing (5330.12, Vols. I-II).

Although formal classroom training is not scheduled at the present time, this handbook contains material that is beneficial to personnel engaged in Nondestructive Testing.

NASA's programs involve tightly scheduled procurement of only small quantities of space vehicles and ground support equipment, requiring the extreme in reliability for the first as well as later models. The failure of one article could result in mission failure. This requirement for complete reliability necessitates a thoroughly disciplined approach to Nondestructive Testing.

A major share of the responsibility for assuring such high levels of reliability lies with NASA, other Government agencies, and contractor Nondestructive Testing personnel. These are the people who conduct or monitor the tests that ultimately confirm or reject each piece of hardware before it is committed to its mission. There is no room for error — no chance for reexamination. The decision must be right — unquestionably — the first time.

General technical questions concerning this publication should be referred to the George C. Marshall Space Flight Center, Quality and Reliability Assurance Laboratory, Huntsville, Alabama 35812.

The receipient of this handbook is encouraged to submit recommendations for updating and comments for correction of errors in this initial compilation to George C. Marshall Space Flight Center, Quality and Reliability Assurance Laboratory (R-QUAL-OT), Huntsville, Alabama 35812.

ACKNOWLEDGMENTS

This handbook was prepared by the Convair Division of General Dynamics Corporation under NASA Contract NAS8-20185. Assistance in the form of process data, technical reviews, and technical advice was provided by a great many companies and individuals. The following list is an attempt to acknowledge this assistance and to express our gratitude for the high degree of interest exhibited by the firms, their representatives, and other individuals who, in many cases, gave considerable time and effort to the project.

Aerojet-General Corp.; Automation Industries, Inc., Sperry Products Division; AVCO Corporation; The Boeing Company; The Budd Co., Instruments Division; Douglas Aircraft Co., Inc.; Dr. Foerster Institute; General Electric Co.; Grumman Aircraft; Mr. John Hall; Mr. Richard Hochschield, Microwave Instruments Co.; Mr. H. L. Libby, Lockheed Aircraft Corp.; Magnaflux Corp.; Magnetic Analysis Corporation; The Martin Co. (Denver); McDonnell Aircraft Corp.; North American Aviation, Inc.; Pacific Northwest Laboratories, Batelle Memorial Institute; Rohr Corporation; Southwest Research Institute; St. Louis Testing Laboratories, Inc.

CLASSROOM TRAINING HANDBOOK
EDDY CURRENT TESTING

CHAPTER 1: INTRODUCTION
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CHAPTER 1: INTRODUCTION

100 GENERAL

1. The complexity and limited procurement on NASA programs and projects dictates a total reliability approach to the task of designing, developing, testing, and producing space vehicles and associated ground equipment. The techniques of nondestructive testing (NDT) are a significant factor in achieving the objective of maximum reliability.

101 PURPOSE

This handbook provides a fundamental knowledge of eddy current principles. The information contained herein will enable NDT quality assurance and test personnel to evaluate test requirements; verify that the proper test technique or combination of techniques are being used to assure the quality of the articles and materials under test; interpret the results of eddy current tests; and recognize those areas of test results that require either retest or further evaluation.

102 DESCRIPTION OF CONTENTS

1. ARRANGEMENT

a. Chapter 1: Introduction, advantages and limitations, testing, personnel, and safety considerations

b. Chapter 2: Eddy current principles and basic electrical concepts related to eddy current testing

c. Chapter 3: Eddy current equipment, coils (absolute differential), types of presentations - meter, cathode ray, tube strip recorder

d. Chapter 4: Eddy current techniques, conductivity, discontinuity, and coating thickness testing; phase and modulation analysis; and applications.

e. Chapter 5: Method control, low conduction materials, conductive liquids and gases

f. Chapter 6: Special applications, dimensions and conductivity measurements, edge discontinuity detection

g. Chapter 7: Comparison and selection of NDT processes as related to the detection of various discontinuities.

2. LOCATORS

The first page of each chapter consists of a table of contents for the chapter. Major paragraphs, figures, and tables are listed in each table of contents.

103 INDUSTRIAL APPLICATIONS OF EDDY CURRENT TESTING

Eddy current testing can be applied to cylinders, tubing, sheets and coatings, and provides a means for measuring conductivity, detecting discontinuities, and determining the thickness of coatings or plating on articles. Since a continuous indication is a part of the basic testing system, automatic production testing is particularly feasible. Test and indication are, for all practical purposes, simultaneous.

104 BASIC EDDY CURRENT TESTING

Eddy current testing is the process of inducing small electrical currents into a conductive article and observing the interaction between the article and the currents. A number of factors within the article will affect the flow of these eddy currents and means exist for relating test indications to these factors.

105 ADVANTAGES AND LIMITATIONS OF EDDY CURRENT TESTING

1. ADVANTAGES

a. Accurate measurement of conductivity

b. Immediate indication

c. High speed testing

d. Detection of small discontinuity areas (e.g., 0.00006 square inches)

e. Non contacting.

2. LIMITATIONS

a. Specific nature of discontinuities are not clearly identified

b. Depth of penetration restricts testing to depths of less than one quarter inch in standard cases

c. Testing of ferro-magnetic metals is sometimes difficult

d. A permanent record of discontinuity is often not available.

106 DESTRUCTIVE AND NONDESTRUCTIVE TESTING

1. DESTRUCTIVE TESTING

Destructive testing as compared to nondestructive testing requires that the test article be loaded and/or sectioned to destruction so as to verify and/or establish engineering design requirements.

Often such a procedure is used to correlate various NDT discontinuities (size and location) to structural or service life of an article.

2. NONDESTRUCTIVE TESTING

Five methods of nondestructive testing are currently in common use: magnetic particle, liquid penetrant, eddy current, ultrasonic, and radiographic. Each method has peculiar capabilities and limitations qualifying it for specific uses. It is necessary to analyze each test article and determine which test method or NDT process will best obtain the desired results. In many instances more than one method may be required. For each article requiring testing, the determination of the proper test method, or methods, is made by qualified NDT personnel.

107 TESTING PHILOSOPHY

The basic reason for nondestructive testing is the ability to test, without damage, all components in production, and thereby assure maximum reliability. Specifically, the space vehicle, with its thousands of square feet of thin metal sheet, thousands of feet of large and small diameter tubing, and many small articles must be checked for complete reliability. With qualified personnel and test equipment, the reliability of all components can be assured. Test standards are high and the test equipment and personnel must be capable of producing results that measure up to these standards.

108 PERSONNEL

It is imperative that personnel responsible for eddy current testing be trained and highly qualified with a technical understanding of the test equipment, the item under test (article), and the test procedures. To make optimum use of eddy current testing, NDT personnel conducting tests must keep abreast of new developments.

109 TESTING CRITERIA

Eddy current testing should be performed using approved written procedures authorized by the using agency. Test and quality assurance personnel should be governed by the using agency with specific instructions and approved test data.

110 TEST PROCEDURES

Approved procedures for eddy current testing are formulated from analysis of the test article, review of past history, experience on like or similar articles, and information available concerning similar article discontinuities. It is the responsibility of personnel conducting or checking a test to insure that test procedures are adequately performed and that the test objective is accomplished.

111 TEST OBJECTIVE

The objective of eddy current testing is to:

a. Insure product reliability.

b. Provide test data that can be evaluated against an acceptable reference standard.

c. Identify and reject unacceptable articles.

d. Evaluate test results to determine the source and cause of article discontinuities.

e. Revaluate test standards and procedures for continued product improvement.

112 SAFETY CONSIDERATIONS

Eddy current testing uses alternating current sources; therefore, normal electrical precautions should be observed. Eddy current testing does not present unique safety hazards to personnel.

CHAPTER 2: EDDY CURRENT PRINCIPLES
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CHAPTER 2: EDDY CURRENT PRINCIPLES

200 GENERAL

This chapter presents basic principles related to eddy current techniques, interpretations, and applications. The depth of presentation is oriented to the eddy current NDT specialists, not to the personnel responsible for the design of initial eddy current testing systems. The reader should realize that each test situation is a separate eddy current design problem. This problem is solved by designing an eddy current testing system for the particular test situation. Once the system is designed and testing procedures are established, the task becomes one of performing eddy current testing in accordance with the established and approved procedures. This is the task of the NDT specialists.

1. DEFINITION OF EDDY CURRENTS

Any eddy current is defined as a circulating electrical current induced in a conducting article by an alternating magnetic field. As the magnetic field alternates, so does the eddy current (reverses). This eddy current flow is limited to the area of the inducing magnetic field. Figure 2-1 illustrates a typical eddy current induced in an article by a test coil on the surface of the article. Note that eddy currents travel parallel to the surface.

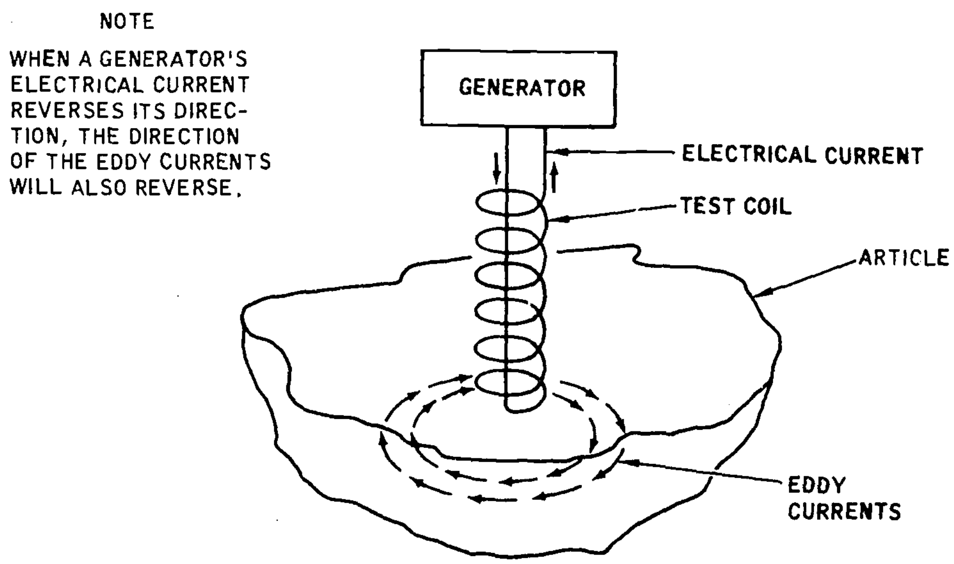


Figure 2-1. Eddy Currents in Article

2. SYSTEM - EDDY CURRENT

As shown in Figure 2-2, eddy current testing is a nondestructive testing system which applies a testing medium to an article and through the article's reaction to the testing medium obtains an output indication.

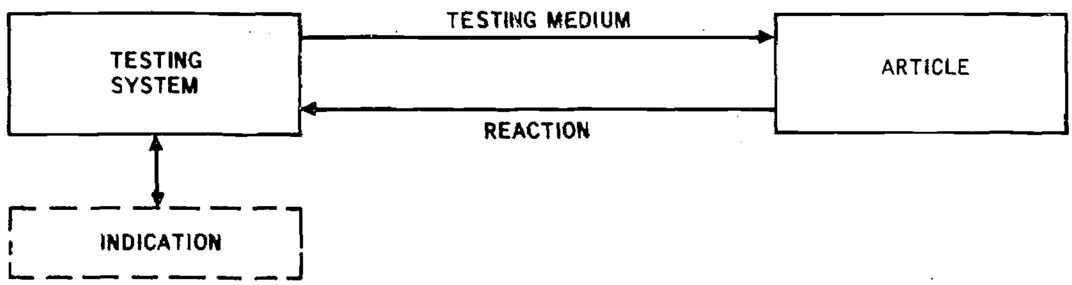


Figure 2-2. Eddy Current System

3. SYSTEMS ELEMENTS

The basic elements of such a system, as shown in Figure 2-3, are a test coil, a generator, and an indicator.

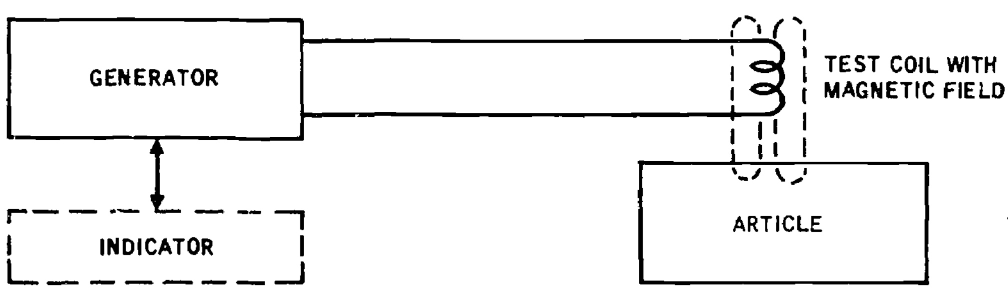


Figure 2-3. Elements of Eddy Current System

Since the NDT specialist is interested primarily in the test coil application and the output indications, we will examine these elements more closely.

a. Test Coil. The basic working element of the eddy current sensing system is a test coil. Some common test coil terms are:

(1) Magnetic field. As an alternating current flows through the test coil, a corresponding electromagnetic field is generated. This alternating magnetic field induces a flow of eddy currents within the article.

(2) Absolute coil. A single coil used to measure bulk article characteristics, e.g., conductivity, dimension, permeability, etc.

(3) Differential coil. The term applied to the use of two coils (usually), that electrically oppose each other. Bulk characteristics of the article will cancel out, but small defects will show as a difference between coils.

(4) Shape. The test coil's geometry establishes the magnetic field required to give the maximum response to the required test.

(5) Surface coil or probe. The term used for those coils designed to be applied on the surface of the article.

(6) Inside diameter coil. The term used for those coils which are designed to be inserted within a specific cavity configuration such as interior of tubing, drilled holes, etc.

(7) Encircling coils (feed through). The term used for those coils designed to be placed around the article.

b. Indicators. Eddy current testing can be divided into three broad areas of presentations:

(1) Meter. This method uses the impedance approach.

(2) Cathode Ray Tube. This method uses the phase analysis approach.

(3) Strip recorder. This method uses the modulation analysis approach.

201 FACTORS AFFECTING EDDY CURRENT TESTING

1. GENERAL

The primary problem in eddy current testing, more so than in any other form of nondestructive testing, is the large number of known or unknown variables which appear in the output indication. These variables permit, limit and/or restrict the use of eddy current testing. At the same time they demand the development of highly specialized eddy current equipment, designed for the separation of variables of interest from all others. The following paragraphs review these variables, identifying their characteristics as related to eddy current testing.

2. CONDUCTIVITY

a. General. One of the main variables in eddy current testing is conductivity. This variable permits the screening of certain materials based upon their conductivity; the detecting of changes in chemistry, lattice distortion and dislocation, heat treat, hardness, discontinuities, etc.

b. Definition of Conductivity. Conductivity is the measure of the ability of electrons to flow through the atomic lattice of a material. The higher the conductivity, the greater the number of electrons which can pass through the material in a given amount of time. Each element or material has a unique conductivity value, e.g., copper, silver and gold have high conductivities, whereas, carbon has a very low conductivity.

c. Eddy Current/Electrical Conductivity Relationship. An eddy current is a flow of electrons. The amount of electron flow through an electrically conductive material is directly related to the conductivity of that material. If the conductivity increases, the flow of eddy current increases. Conversely if the conductivity decreases, the flow of eddy current decreases.

d. Conductivity/Resistance Relationship. Resistance is defined as the opposition to the flow of electrical current (electrons). Often the term resistance is used rather than the term conductivity. One is the reciprocal of the other. For example, one can say that an increase in conductivity is the same as a decrease in resistance. Or a decrease in resistance is an increase in conductivity.

e. Conductivity Expressed in Terms of IACS. Conductivity can be expressed in terms of the International Annealed Copper Standard (IACS). This standard is based on a specific grade of high purity copper, which is defined as having an electrical conductivity of 100 percent. Other materials are defined as a percentage of this standard, e.g., pure aluminum has an IACS of 66% - alloy this aluminum with copper and the IACS will change to another value, e.g., 50%.

f. Measurement of Conductivity. Direct measurement of electrical conductivity for eddy currents is a very time consuming task. It involves directing an oscillating magnetic field into a material perpendicular to its surface. This oscillating magnetic field causes oscillatory motion of the electrons in the material. The number of electrons and the distance they travel during a single cycle is dependent on the electrical conductivity of the article. The moving electrons in turn generate a countering or opposite magnetic field perpendicular to the article's surface and decreases the intensity of the directed magnetic field. Electronic circuitry is provided to measure the change in intensity of the directed magnetic field. Such a unit is calibrated to read in units of electrical conductivity.

Eddy currents provide a means for accurately measuring the comparative conductivity of a material. All other factors being equal, the flow of eddy current is directly related to the material's conductivity. It thus becomes possible to manufacture equipment which contains a scale marked in terms of the IACS percentage. Such conductivity testers provide a means of measuring conductivity directly in terms of this percentage. Test procedures can be written which specify acceptable conductivity by this percentage.

g. Variables Affecting Conductivity. Many variables affect an article's conductivity. This is both an advantage and a limitation. Actually there are so many variables that affect conductivity that measurement is a problem. An accurate eddy current test requires isolation of the one variable required and elimination of the others from the test indicator. Variables which affect conductivity are:

(1) Chemical Composition. Any pure basic element has a conductivity determined by its perfect atomic lattice and thermal motion of the atoms. Thermal motion of these atoms hinders movement of electrons through the material by adding additional obstacles. Different elements are made up of varying numbers of atoms which are arranged in a variety of orders thereby resulting in various types of building blocks composing the elements, e.g., copper, iron, cobalt, etc.

This difference between elemental lattices provides the prime variable for determining conductivity.

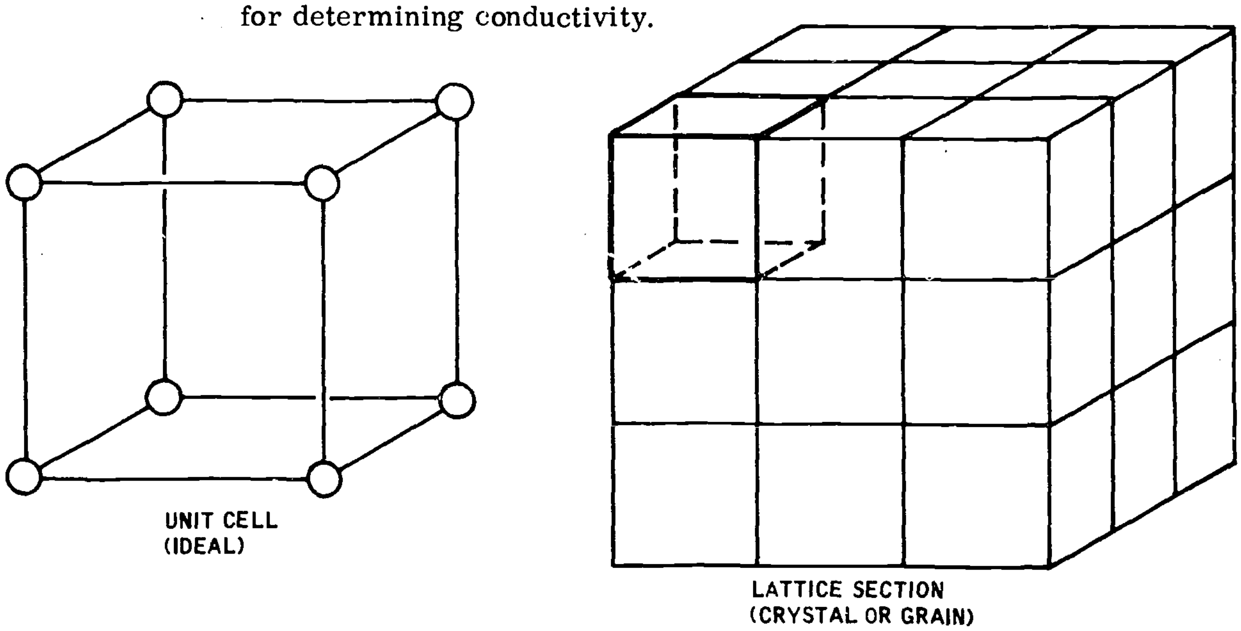


Figure 2-4. Pure Element Lattice Structure

(2) Alloy Composition/or Impurity Content. It is possible to identify base metals by the conductivity of their lattice structure, however, since base metals are rarely used as such, it is more useful to identify the various alloys of base metals than to identify the base metals themselves. These alloys are combinations of impurities (other metals/ chemical elements) and a base metal. When impurities are added to the base metal, they tend to distribute randomly throughout the pure lattice structure destroying the normal order and altering the original conductivity of the base metal. (Figure 2-5.) Each impurity or combination has an individual effect on the conductivity of the base metal. The conductivity of the resultant alloy is a collective value which is directly related to the chemical/metallic composition of the alloy. Alloy composition of certain alloys may be determined by conductivity where alloying elements increase or decrease the conductivity of the alloy.

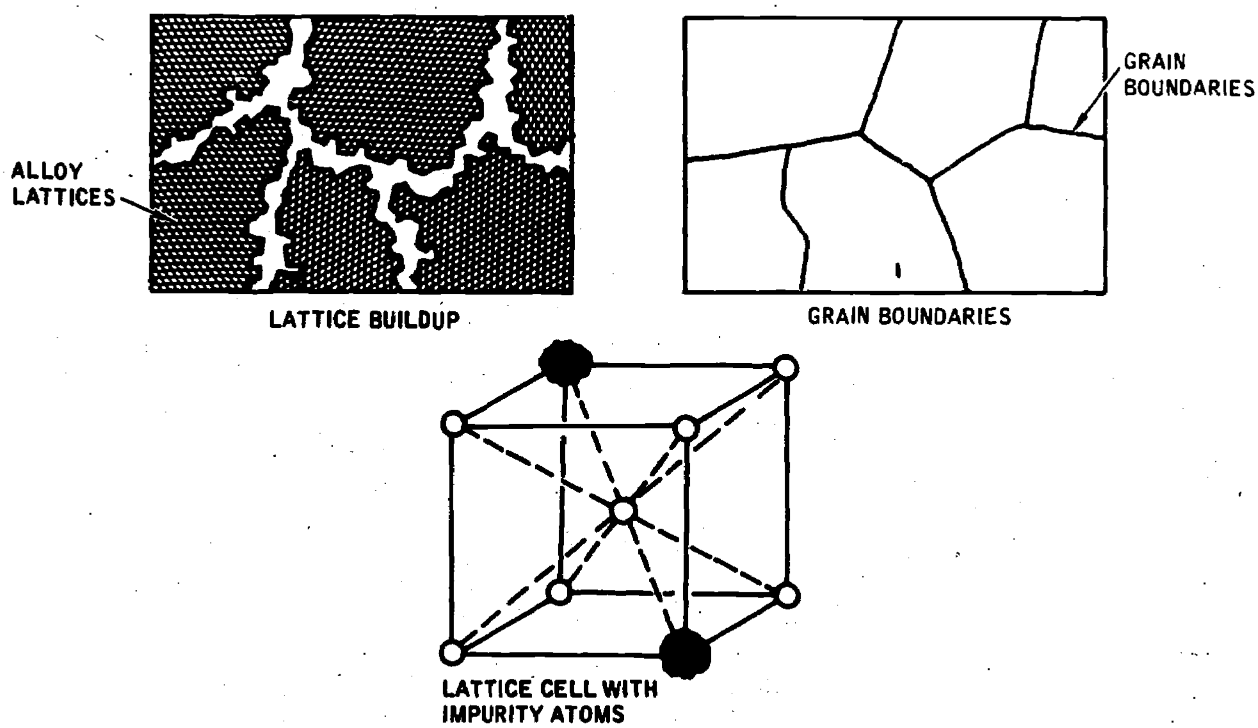


Figure 2-5. Impurity in Lattice Atom

(3) Heat Treatment. During the heat treatment a redistribution of the elements is made in the material as shown in Figure 2-6. The degree to which they go into solution is dependent upon the temperature and time. Too low a temperature and too short a time will result in the incomplete solution of the hardening elements in, for example, aluminum. This will in turn result in low physical properties and unsatisfactory aging characteristics. Too high a temperature can cause an equally drastic metallurgical reaction, e.g., excessive grain size. These changes can often be monitored by conductivity values which have been established for the specific alloy after solidification.

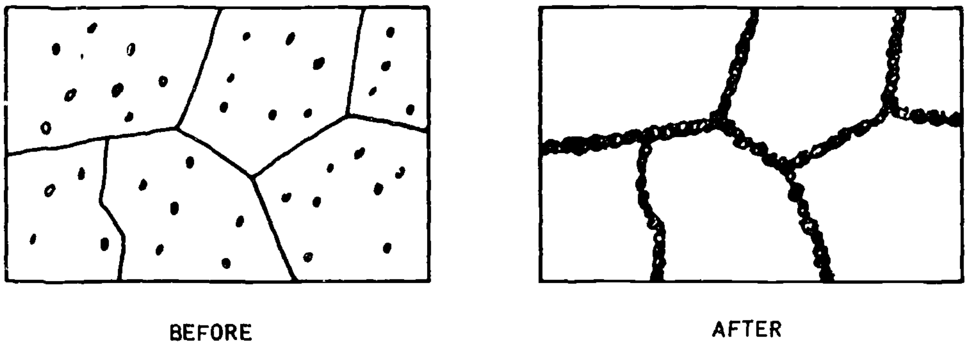


Figure 2-6. Heat Treatment Affect on Elements

(4) Quenching. The most critical aspect of heat treating is the quenching operation. A delay in quenching, improper quenching temperature, agitation, etc., can result in the freezing of the desirable elements (constituents) in solution resulting in adverse metallurgical properties.

(5) Lattice Distortion/Dislocation. During any cold working operation a degree of lattice distortion and dislocation takes place. (Figure 2-7). This mechanical process changes the location, size and shape of the grain within the material. Such dislocation increases the hardness of the material thereby changing the conductivity value for the material being tested.

(6) Lattice Defects. Any defect in the lattice of the article due to hardness, stressing, radiation, etc., directly alters the conductivity of the article. At times this can be used as a basis for measuring lattice altering conditions.

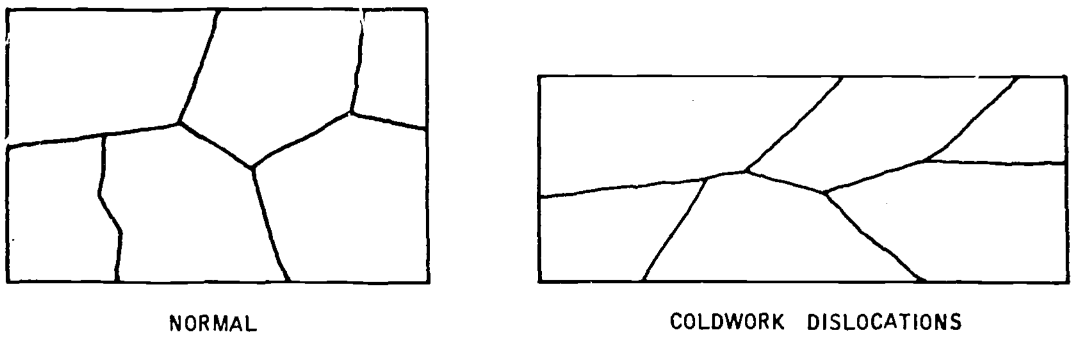


Figure 2-7. Lattice Distortion

(7) Temperature. A definite relationship exists between the temperature and electrical conductivity of a material. As shown by Figure 2-8, a temperature increase will result in an increase (swelling) of the lattice structure. This increased size of the lattice structure and thermal motion of the atoms will decrease the conductivity of the material. Where the conductivity value is critical and tolerance is small, the temperatures of the article and control article should be specified.

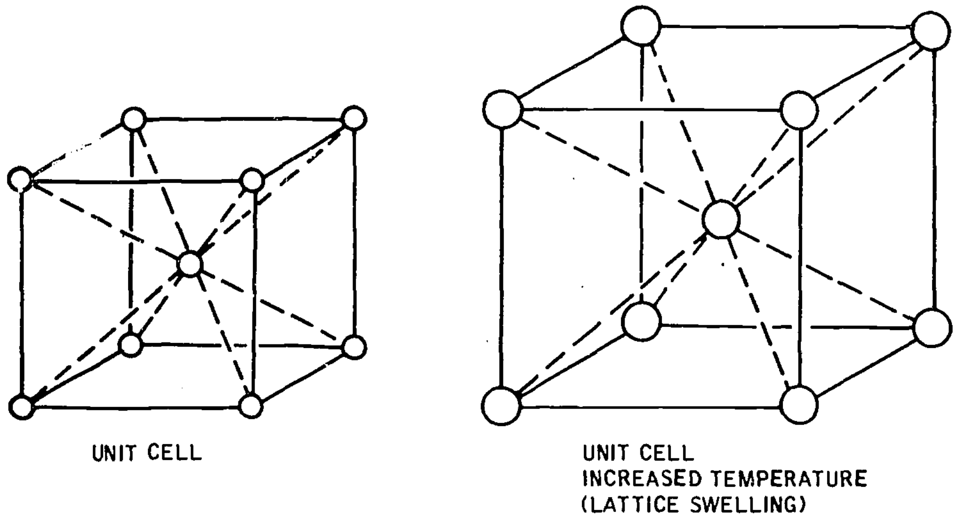


Figure 2-8. Lattice Swelling

(8) Discontinuties. The flow of eddy current within the article is affected by the conductivity in the area near the test coil. Any discontinuity in this area will alter the eddy current flow. (Figure 2-9). Discontinuities, such as inclusions, cracks, porosity, affect the eddy current flow in that local area and will cause a decrease in electrical conductivity.

Example

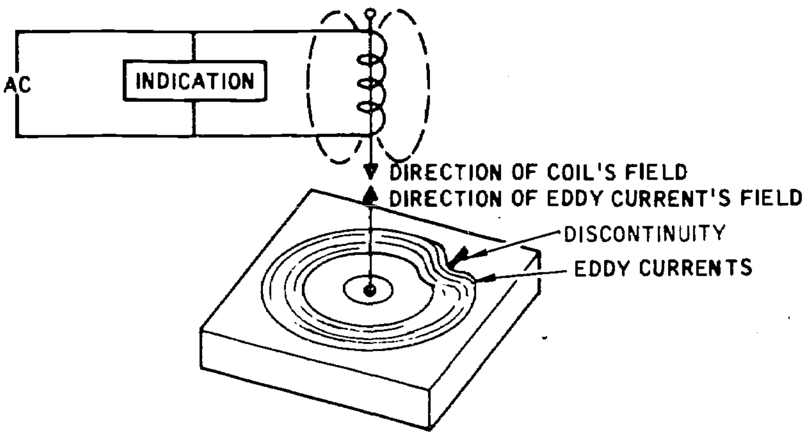


Figure 2-9. Distortion of Eddy Current Wave Pattern

3. PERMEABILITY

a. General. In performing eddy current testing it is important to know whether the article is magnetic or nonmagnetic. The difference between a magnetic material and a nonmagnetic material is the relative ease with which the magnetic domains align themselves and is a factor called "permeability." Permeability has a much greater effect on the test coil than does conductivity. Therefore, its presence can mask all other measurements. The permeability factor can be suppressed or made constant by applying a DC bias to maintain alignment of magnetic domains.

b. Magnetic Domain. The degree of individual magnetic response will vary widely from nonmagnetic to magnetic materials.

Magnetism occurs at the atomic level. The planetary spin of the electrons around the nucleus, and the off-balance condition in the incomplete shell, together within their specific dimensional characteristics, create a magnetic moment (a measure of the magnetizing force).

The movement of the inner atoms are held parallel by quantum mechanical forces, e.g., planetary bodies are held in position because of a like force. The atoms of a metal showing magnetic characteristics are grouped into regions called domains. A domain is the smallest known permanent magnet.

In nonmagnetic materials an equal number of electrons spin clockwise and counterclockwise about their axis. This results in no internal motion and no noticeable magnetic domain.

In magnetic materials more electrons spin in one direction than in the other. This unbalanced condition of electron spin creates a magnetic moment which makes the atom a small magnet. In unmagnetized magnetic materials, the domains are randomly oriented and neutralize or produce no observable magnetism. (Figure 2-10, View A).

Subject ferromagnetic materials to an external magnetic field and the randomly oriented magnetic domains start to align themselves so that their magnetic moments combine with the applied field. (Figure 2-10, View B).

Materials having a high permeability, such as iron, nickel and cobalt, retain only a small domain alignment when the external field is removed.

However, materials with low permeability, such as ALNICO (aluminum, nickel, iron alloy) require a stronger external force to establish domain alignment. These materials will retain a much higher percentage of domain alignment after removing the external force (Figure 2-10, View C).

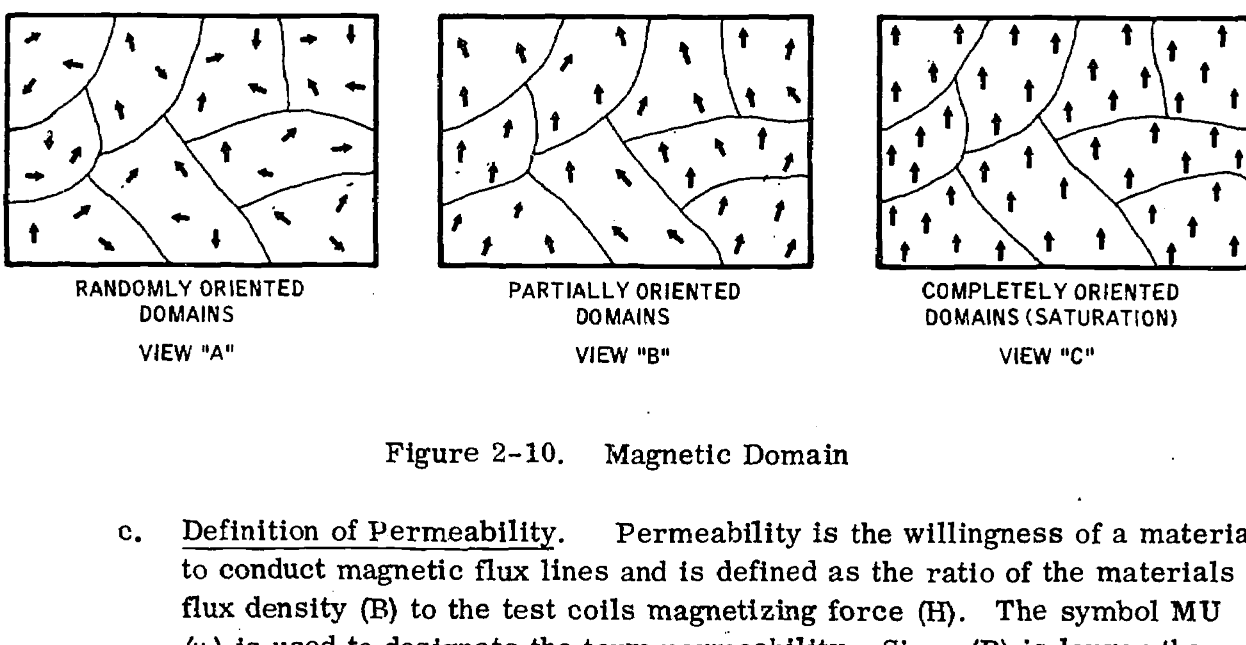
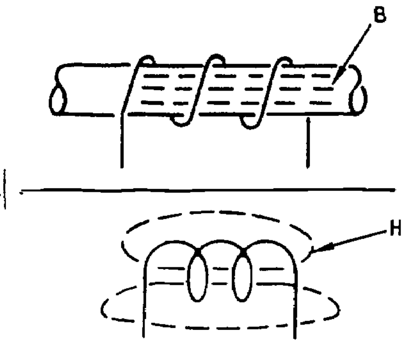


Figure 2-10. Magnetic Domain

c. Definition of Permeability. Permeability is the willingness of a material to conduct magnetic flux lines and is defined as the ratio of the materials flux density (B) to the test coils magnetizing force (H). The symbol MU (μ) is used to designate the term permeability. Since (B) is larger than (H), permeability will be greater than one. (Figure 2-11).

PERMEABILITY = $\frac{B}{H}$ OR μ =



$\mu = \frac{\text{FLUX DENSITY}}{\text{MAGNETIZING FORCE}}$

Figure 2-11. Permeability

It's interesting to note some selected values for permeability. They can range from approximately one to many thousands.

K-Monel	1+
Wrought Iron	2,000
High Silicon Steel	9,000

Note: Permeability of air μ = 1.0

since $\frac{B}{H} = 1.0$

(1) B Increases as H Increases. Permeability is often described by the use of a graph as shown in Figure 2-12. The horizontal scale represents the coil's magnetizing force H. Since this force reverses itself (O to H then H to O to H') the scale is represented by the values H and H'. The vertical scale represents the material's flux density B. Again, since the flux reverses its direction as H reverses the scale is shown as B and B'. The initial curve O to A represents the initial application of the coil's magnetizing force to the material. As shown by this curve, B increases as H increases until the material is magnetically saturated.

For a magnetic material, equal changes in magnetic force (or AC) do not produce equal changes in flux density (B). This can be seen in Figure 2-12.

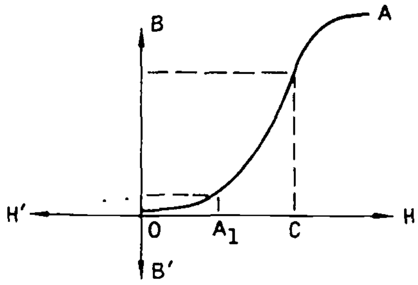


Figure 2-12. Flux Density

If the magnetizing force increases, the material will be partially magnetized and only a small value of B is developed due to the initial resistance of the domains to align themselves. If the force now moves from A_1 to C, B rises to a large value due to the relative ease with which the domains now align themselves.

(2) Permeability is not Linear. Since curve OA is not a straight line, the ratio of B to H is not constant (not linear). Equal changes in H do not cause equal changes in B. Because the material's flux density B affects the eddy currents, the permeability is introducing a variable into the eddy current testing system. This permeability variable interferes with the eddy current indications.

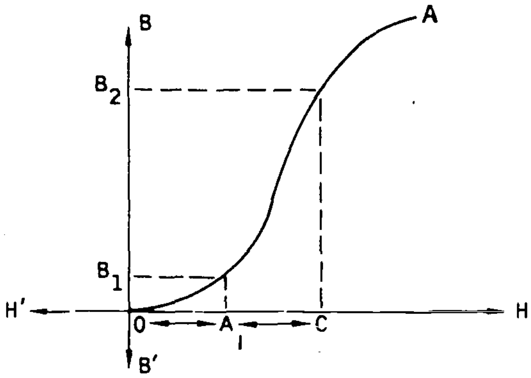


Figure 2-13. Unequal Changes in Flux Density

In Figure 2-13, the magnetizing force is H and the flux density is B. The value OA_1 represents a specific change in the magnetizing force H. This change produces the flux change OB_1.

If now, a second change in magnetizing force is made (e. g. , AC) then a change in the flux density B will occur. The change A_1 to C produces the change B_1 to B_2. Note that the flux change B_1 to B_2 is greater than the flux change O to B_1.

Since the magnetizing force change A_1C is the same as OA_1, this means that equal changes in magnetizing force produced unequal changes in flux density.

(3) Saturation. As H is increased, B increases. As shown in curve OA (Figure 2-14) a point is finally reached where further increase of H does not cause further increase in B minus H value. This point is referred to as the saturation point (A).

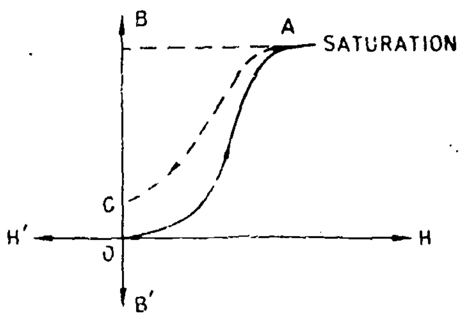


Figure 2-14. Saturation Magnetic Point

(4) Residual Magnetism. The coil's magnetic field reverses itself in accordance with the alternating current and the maximum value of H will decrease to zero (point 0) and increase to a maximum value (H') in the reverse direction. As H decreases to zero (point 0) the material's flux density decreases, as shown in Figure 2-15, however, this decrease does not follow the initial curve OA. Because of residual magnetism, the decrease in B follows the curve AC. When H is at a zero value (point O), flux density still exists within the material. This is defined as the residual magnetism of the material. Under this condition, the material may have residual fields like a natural magnet.

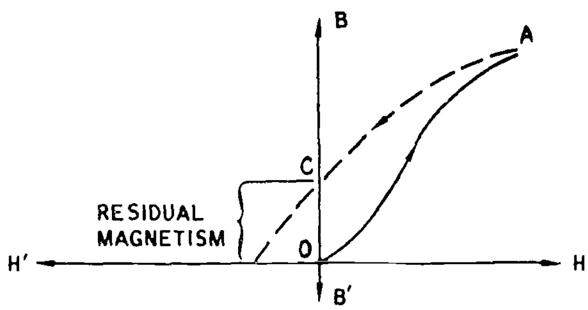


Figure 2-15. Residual Magnetism

(5) Coercive Force. The magnetizing force required to reduce the material's flux density to zero is called the coercive force. The coercive force must be applied in the opposite direction to the initial magnetic force. (Figure 2-16).

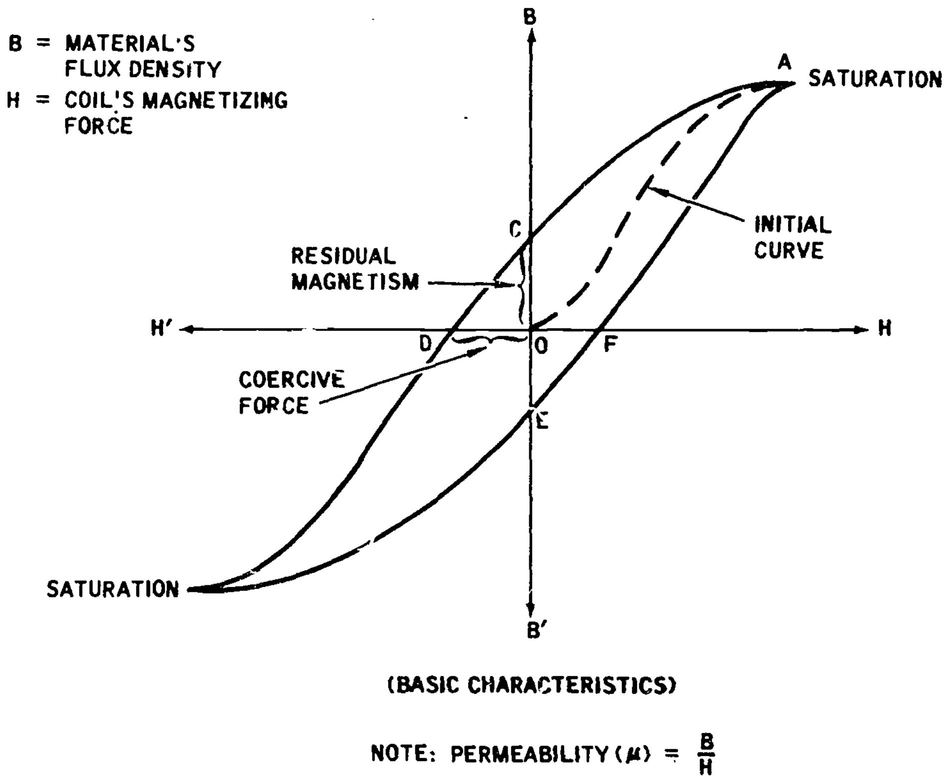


Figure 2-16. Coercive Force

(6) Hysteresis Loop. A periodically reversing magnetic field produces a loop as shown in Figure 2-17. The characteristics of the loop are the same in either direction. Thus saturation, residual magnetism, and coercive force are terms that apply in both directions. The shape of the loop as well as the size of the loop is used to define the magnetic characteristics of a specific magnetic material. This loop, referred to as a hysteresis loop, can be observed through the use of a cathode ray tube.

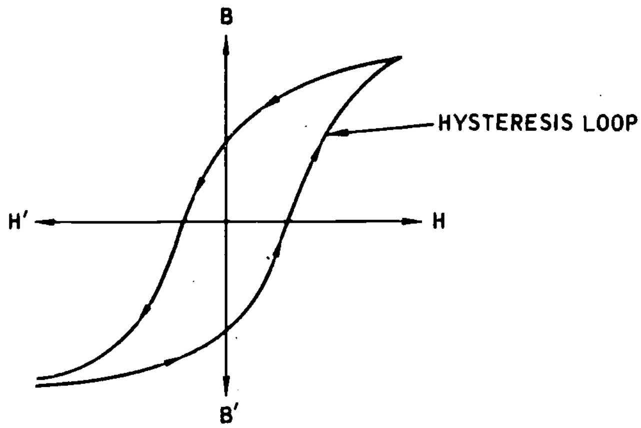


Figure 2-17. Hysteresis Loop

d. Coil's Magnetizing Force. A coil's magnetic field is viewed as a distribution of lines of force around the coil. The number of lines in a unit area is defined as the flux density. This flux density represents the coil's magnetizing force. The letter H is used to denote this force (Figure 2-18). The value of H depends on the number of turns, diameter, length, etc., of the coil and the amount of current applied to the coil.

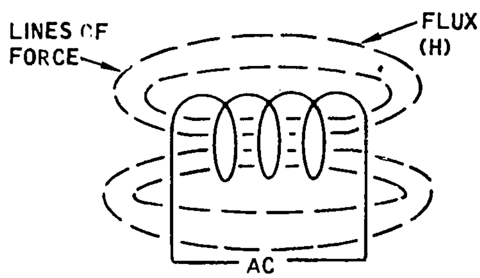


Figure 2-18. Coils Magnetizing Force

e. Flux Density in Nonmagnetic Material. When a test coil's magnetizing force is applied to an article, the coil's flux density enters and becomes established within the article. This causes the flow of eddy currents. The amount of current is directly related to the coil's magnetizing force. In nonmagnetic materials (Figure 2-19) the article does not generate any additional flux density due to the absence of magnetic domains. The only flux density within the article is that which is supplied by the test coil's magnetic field. Under these conditions, it can be said that any changes in eddy currents are caused by the article's conductivity or by the coil's flux density induced in the article.

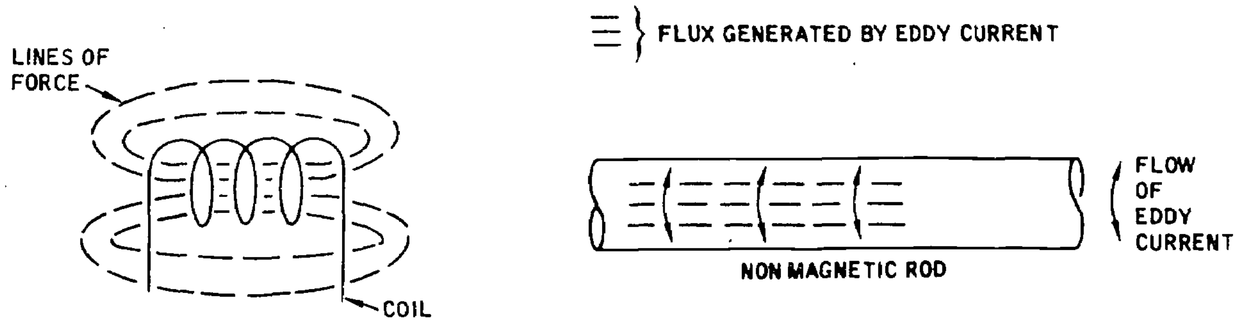


Figure 2-19. Flux Density Nonmagnetic

f. Flux Density in Magnetic Material. When a coil's magnetizing force is applied to a magnetic material, the amount of flux density in the material is greater than the flux density supplied by the test coil (Figure 2-20). This is due to additional flux densities generated by magnetic domains. Such is the nature of a magnetic material. The total flux density in a magnetic material is designated by the letter B. The letter B refers to the flux density generated in the material; the letter H refers to the magnetizing force of the test coil to which the material is subjected.

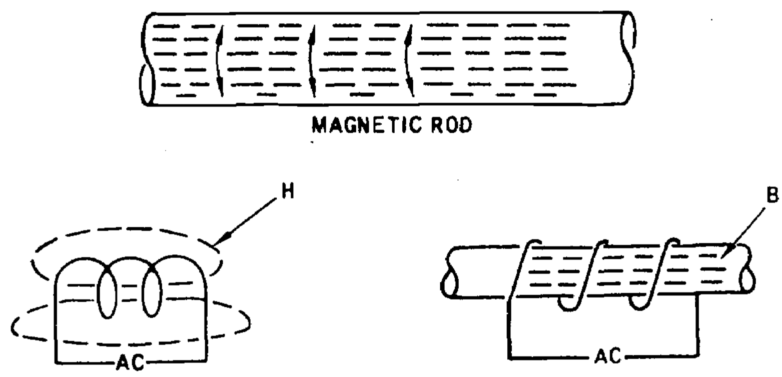
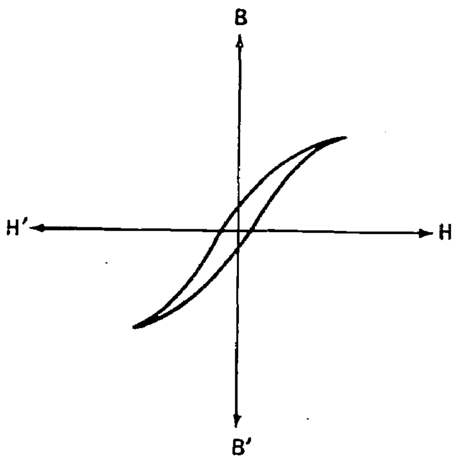
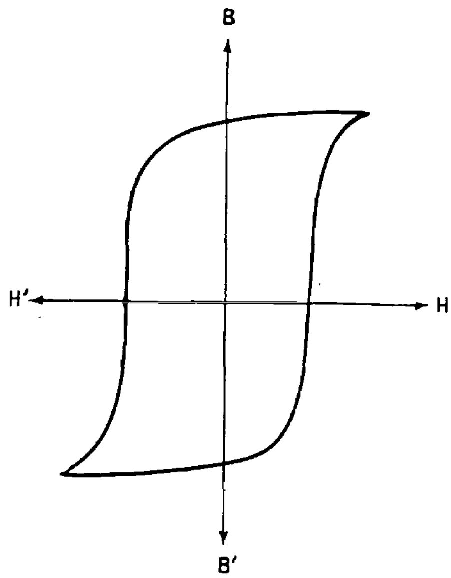


Figure 2-20. Flux Density Magnetic

g. Ferromagnetic Material. It is convenient to classify materials as magnetic or nonmagnetic. Most magnetic materials are called ferromagnetic which means "of or relating to a class of substances characterized by abnormally high magnetic permeability, definite saturation point, and appreciable residual magnetism and hysteresis." Since all materials exhibit some magnetic effects, the difference between a magnetic or nonmagnetic material is one of degree. For example, Figure 2-21 shows two hysteresis loops. The loop for the nonmagnetic material is small and little residual magnetism exists. By contrast, a magnetic material has a large loop with considerable residual magnetism.



(NON MAGNETIC MATERIAL)



(MAGNETIC MATERIAL)

Figure 2-21. Residual Magnetism - Magnetic and Nonmagnetic Materials

h. Effect of Permeability on Eddy Currents. Eddy currents are induced by flux changes within an article and are directly related to the density of the flux. Since a material with a high permeability provides a greater amount of flux than a material with a low permeability, it can be expected that permeability has a definite effect on the amount of eddy currents induced in the article. As the permeability increases, the amount of eddy current increases. This effect is more pronounced than any conductivity effect.

i. Effect of Permeability on Output Indications. The presence of permeability introduces a variable into the output indication. Internal stresses and lattice impurities which can vary within an article, affect the permeability and will be reflected in the permeability variable.

j. Making Permeability a Constant. The permeability variable can be made a constant value by using a direct current coil to maintain domain alignment in addition to the regular test coil. The direct current coil establishes a magnetic field which causes the flux density generated by the magnetic material to remain saturated. Under this condition, the only flux changes within the article will be caused by the test coil. This technique removes the permeability variable from the output indication by making the permeability value negligible.

k. Heating Effects in Magnetic Materials. When a magnetic material is subjected to an alternating magnetic field, heating effects exist within the material. This is caused by the work required to reduce the residual magnetism to zero and by the realignment of the magnetic poles associated with a magnetic material. Such heating can be eliminated by the use of the saturation technique. It should be realized that complete saturation is sometimes not possible in a few materials; thus, the heating effect may be present. This heating effect may influence the conductivity of the material. Note: This effect is noted with older type eddy current testing equipment and not applicable to present day equipment.

4. MAGNETIC COUPLING

a. General. In eddy current testing the article is coupled to the test coil by the coil's magnetic field, all informative interaction is through this coupling. The strength of the coil's field decreases with distance from the coil. The closer the article to the coil, the greater the strength of the applied magnetic field. Therefore, the density of eddy currents in the article varies as the distance between the coil and article. The strength of this field is also dependent on the coil's geometry, i.e., size and shape.

b. Magnetic Fields. In a straight wire (Fig. 2-22) the magnetic field assumes a circular shape, expanding outward from the surface in concentric clockwise circles. To determine the direction of current and magnetic field flow the right hand rule applies. This can be done by grasping a wire conductor in the right hand, the thumb would point in the direction of current flow while the fingers wrapped around the wire determine the magnetic field.

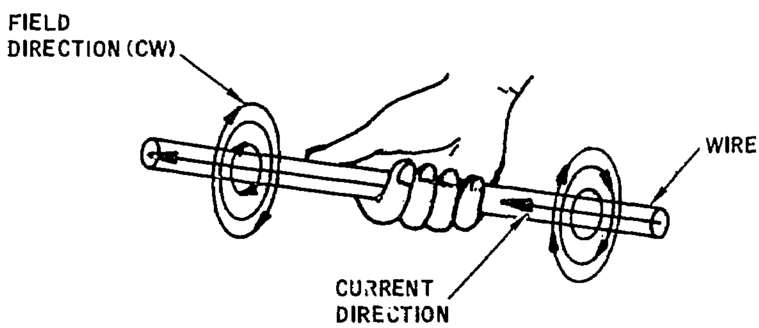


Figure 2-22. Magnetic Field in a Straight Conductor

If this straight wire is now formed into a single circular loop (Figure 2-23), the magnetic fields no longer assume the concentric circular pattern about the wire. The magnetic field will now cut the plane of the wire loop at right angles and at the center of the loop the direction of the magnetic field follows the axis of the loop. Here again by grasping the coil, the fingers will point in the direction of the current while the thumb will point in the direction of the magnetic field. (Figure 2-24). It is quite obvious that a change in wire geometry greatly altered the magnetic field from the original straight wire.

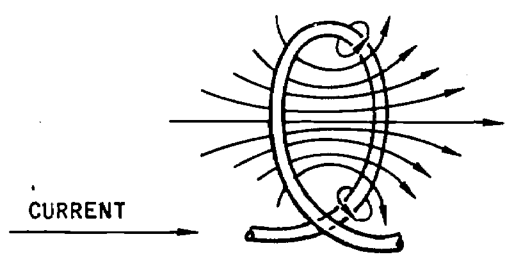


Figure 2-23. Magnetic Field in a Loop

c. Magnetic Field Intensity. Starting with the straight wire we have a field intensity at a given point of H. If this same wire is formed into a single loop the field intensity is increased over the straight wire by the factor π (pi).

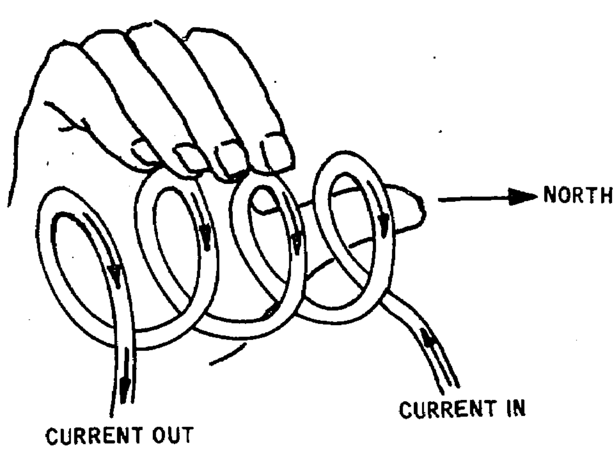


Figure 2-24. Magnetic Field in a Solenoid

If we add several loops close together into a flat coil (probe), the intensity is increased by N (number of turns) times the intensity of our single loop.

The intensity may be further increased in a solenoid, Figure 2-25, where the length of a coil is greater than the diameter of the turns.

By adding a soft iron core to the solenoid, the number of lines of force and, hence, the flux density can be greatly increased without increasing the magnetizing force applied to the solenoid.

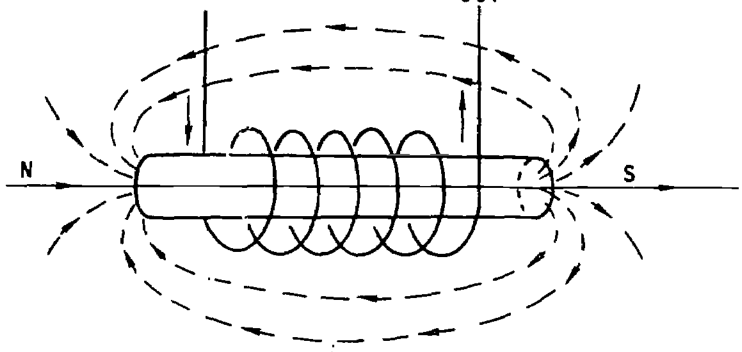


Figure 2-25. Magnetic Field Within Solenoid With Iron Core

d. Lift-Off. The term "lift-off" is used in application of surface type coils and is defined as the large effect on output indication due to the decrease in flux density generated within the article as the coil distance from the article surface is increased. Figure 2-26 illustrates this condition.

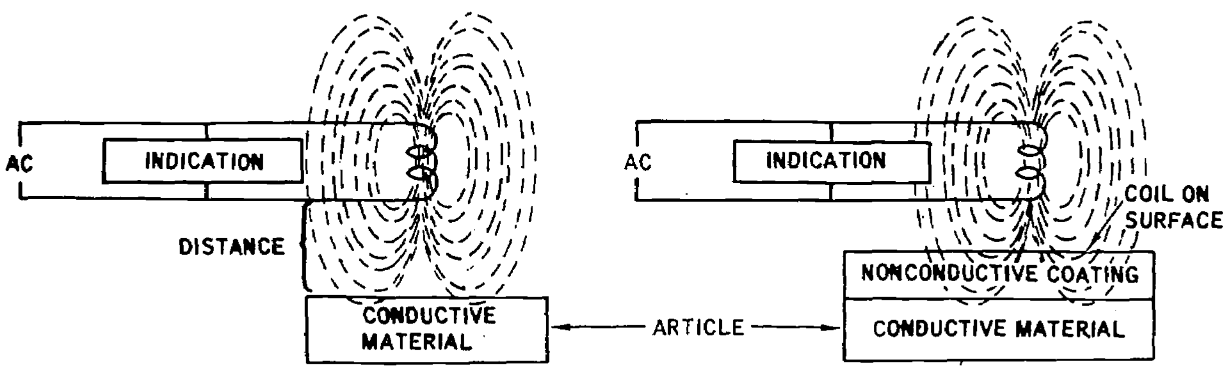


Figure 2-26. Surface Coil Lift-Off

(1) Surface Coil On Conductive Surface. When a surface coil is placed on the surface of a conductive material, a certain amount of lift-off effect still exists. Lift-off is a very sensitive effect and a variation of less than one-thousandth of an inch can cause a change in indication. Special circuits within the eddy current testing equipment can be used to balance out this effect for some measurements. Often surface coils are spring loaded to maintain contact with the surface to hold lift-off constant.

(2) Surface Coil on Non-Conductive Surface. The use of a surface coil on a non-conductive surface is a major application of eddy current testing. While eddy currents do not exist in non-conductive materials, the eddy current lift-off effect can be used to measure the thickness of non-conductive coatings on conductive article. When the coil is placed in contact with the non-conductive coating (Figure 2-27) the thickness of this coating directly constitutes lift-off distance. Since lift-off has a large effect on indication, non-conductive coatings can be measured very accurately.

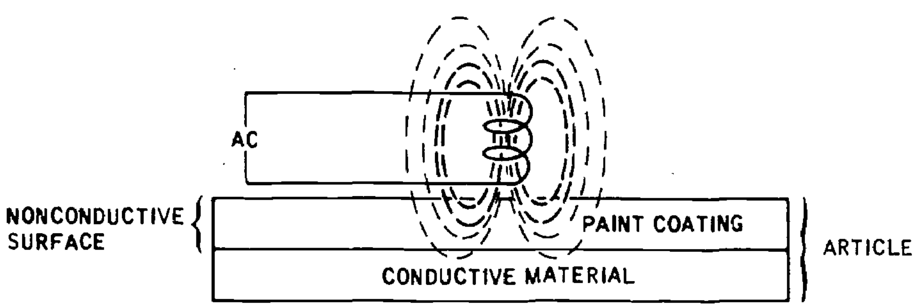


Figure 2-27. Non-Conductive Surface

e. Fill-Factor. For encircling coils (or inside coils) the equivalent of lift-off effect is termed "fill-factor." As shown in Figure 2-28 this factor is the ratio of the article cross-section area to the area of the coil opening and can be expressed as the ratio of the respective diameters squared. To allow freedom of movement through the test coil, this ratio is always less than one.

NOTE

$$\text{FILL-FACTOR} = \left(\frac{D_1}{D_2}\right)^2$$

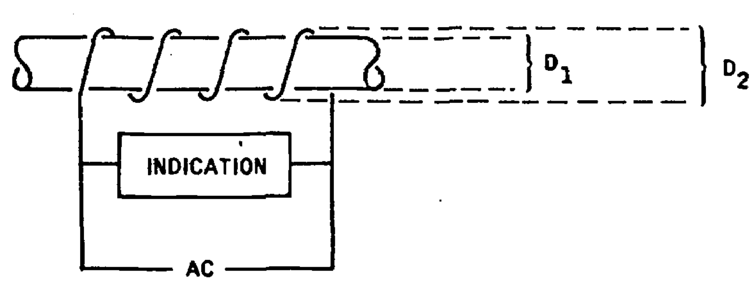


Figure 2-28. Fill-Factor

(1) Need For Centering Article in Coil. Due to difference in D_1 and D_2 the fill factor (lift-off) has changed. This produces a major change in the output indication. It should be noted that a reduction in fill factor also increases fall-off. This increase in fall-off will reduce the established test sensitivity, thereby altering the test conditions.

f. Geometry. In the design of test coils, the "fall-off" of the electromagnetic field due to the coil dimensions must be taken into account. Also, the shaping of such fields by means of magnetic shielding reduces the area of the article covered by the magnetic field. This in turn reduces penetration regardless of the standard penetration depth as selected on the chart. Another effect dependent on coil geometry is "end effect." End effect is experienced when the magnetic field of the coil is near the boundary of the article (end) and air. This distorts the magnetic field so greatly as to mask any measurement data.

(1) Coil Dimension Effect on Magnetic Field. As shown in Figure 2-29, the extension (fall-off) of the magnetic field is a function of the pole size and pole spacing even though lift-off is held constant (surface contact).

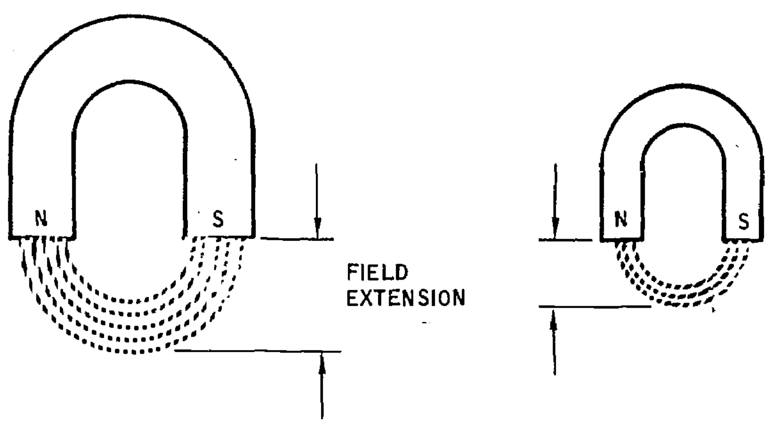


Figure 2-29. Fall-Off

(2) Coil Shielding Effect on the Magnetic Field. As shown in Figure 2-30 pinching or direction of the magnetic field generally reduces the extension of the magnetic field from the coil. This reduction of the magnetic field extension directly lessens the depth of penetration.

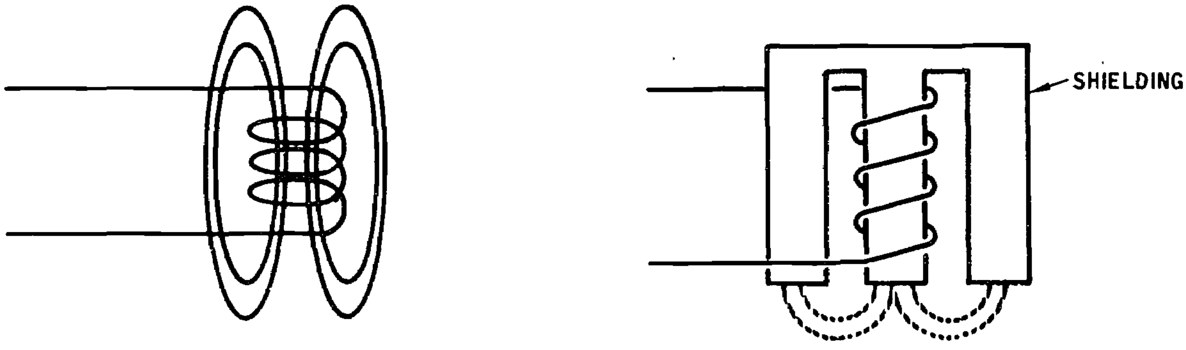
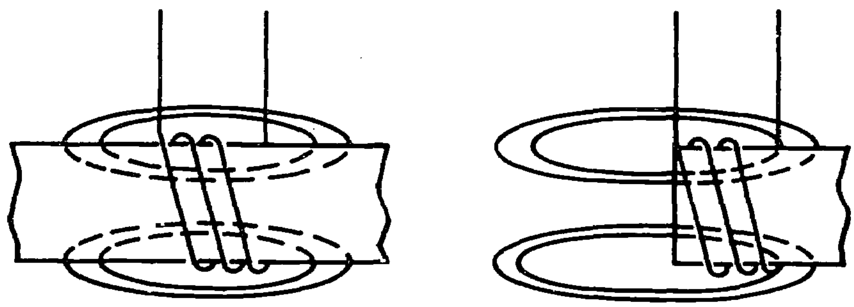
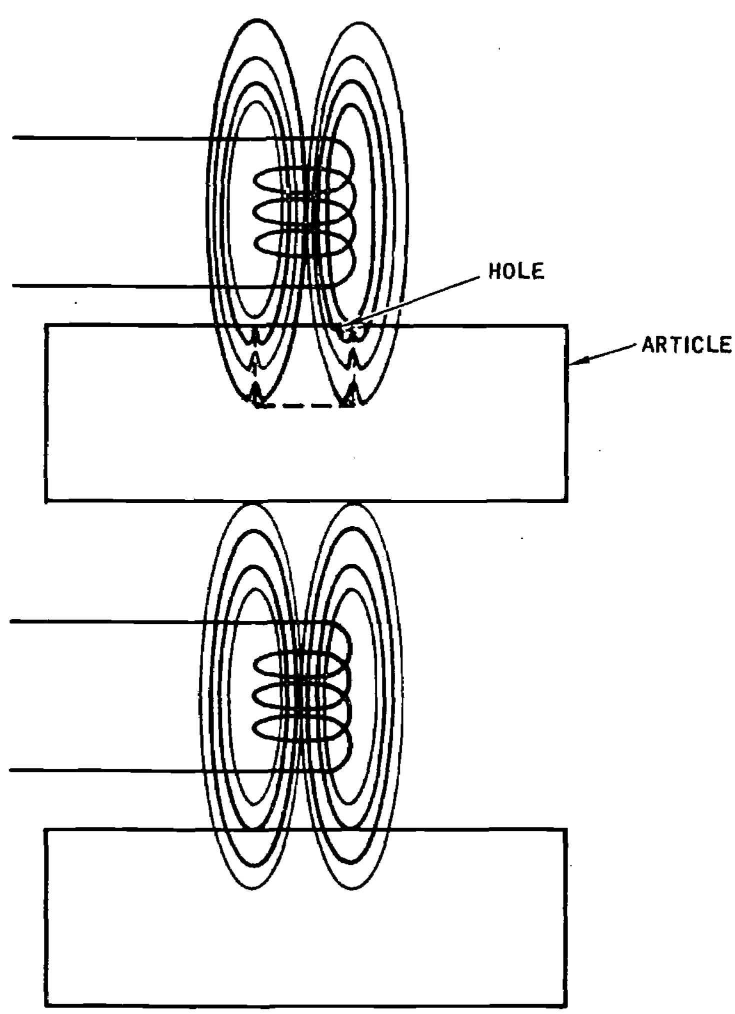


Figure 2-30. Shielding

(3) End Effect on Magnetic Field. As shown in Figure 2-31 if the coil's magnetic field is near an article-to-air boundary, a non-uniform field will result due to difference in the ability of the two media to conduct magnetic flux lines. This distortion masks out most usable measurements. For this reason, coils are usually designed shorter or smaller than the article depending on the type of coil. "End effect" is responsible for difficulties in taking measurements near any such boundary, i.e., holes, edges, tubing ends, etc.



(Encircling Coil)



(Surface Coil)

Figure 2-31. End Effect

202 DIRECTION AND DISTRIBUTION OF EDDY CURRENT IN ARTICLE

1. GENERAL

To successfully perform eddy current testing, the NDT specialist must be aware of the direction and distribution of eddy currents in the article. The direction is determined by the type of coil used in the testing. Eddy current distribution in the article is determined by the frequency used in the testing, the coupling between the coil and the article, and the conductivity and permeability of the article. Eddy currents always flow parallel to the surface.

2. EDDY CURRENTS INDUCED BY ENCIRCLING COIL

As shown in Figure 2-32, when an encircling coil is used, the path of the eddy currents is in the same direction as the windings of the coil. Thus eddy currents tend to flow around the outside circumference of the cylinder and a discontinuity such as a crack will disrupt this flow. You will also note that the center portion of a rod has practically no eddy currents since the magnetic field and eddy currents tend to stay near the surface. Detection of a discontinuity near the center would be difficult or impossible. Because the encircling coil tests the complete circumference of the cylinder, it is not possible to isolate a discontinuity to a specific point on the circumference. Eddy currents induced by this coil show the maximum effect for discontinuities oriented axially.

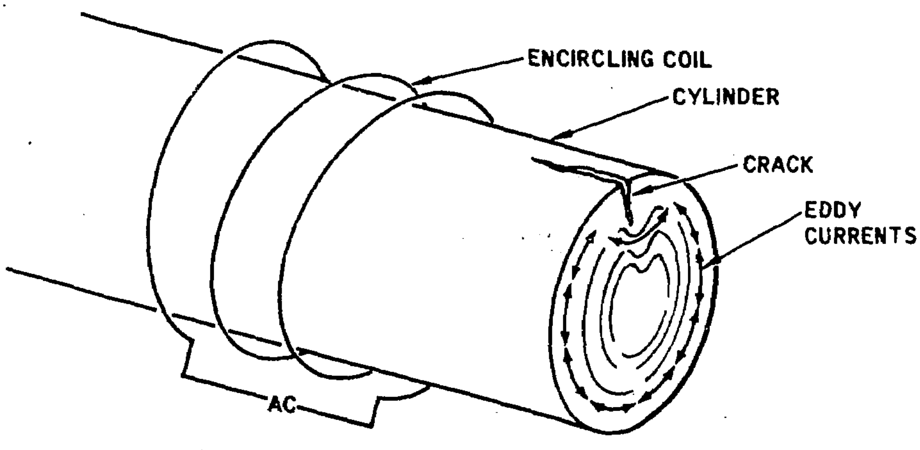


Figure 2-32. Direction of Eddy Current Paths in Cylinder

3. EDDY CURRENTS INDUCED BY INSIDE COIL

Like the encircling coil, the path of the eddy currents induced by an inside coil is in the same direction as the coil winding; therefore, eddy currents flow around the inside diameter of the cylinder.

4. EDDY CURRENTS INDUCED BY SURFACE COIL

Figure 2-1 illustrates the direction of eddy currents induced in an article by a surface coil placed above the article's surface. The eddy currents will flow in a direction that is parallel to the article's surface.

5. EDDY CURRENTS INDUCED BY GAP PROBE

The gap probe provides a very concentrated magnetic field. This induces eddy current in a small area. The smaller the airgap, the more concentrated is the flux density between the poles. Any discontinuity within this area greatly alters the magnetic field produced. This type of probe can also provide location of the discontinuity in the article.

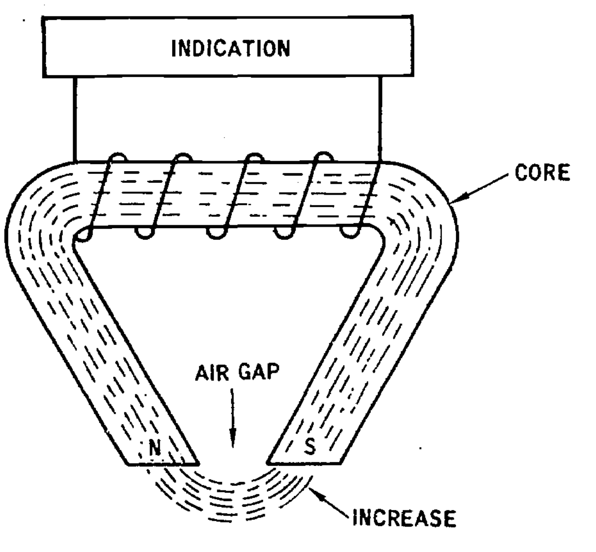


Figure 2-33. Eddy Currents Induced by Gap Probe

6. DEPTH OF EDDY CURRENT PENETRATION

Penetration of the eddy current in an article must be a known factor to interpret indications. Eddy currents are strongest near the surface and weaken with depth. They often have a penetration depth less than one quarter of an inch in standard cases. This "skin effect" is directly affected by the inducing frequency, the higher the frequency the less the depth of penetration.

In practice, since we cannot achieve uniform induced fields, we resort to a standard depth, defined as the depth where the eddy current is reduced to 1/e (approximately 37%) of the surface current. This concept allows a tabulation of depths based on frequency (time), conductivity and permeability.

a. Relationship Between the Coil's Magnetic Field Strength and Eddy Current Density. The eddy current density is related to the strength of the coil's magnetic field. As this field strength decreases, the eddy current density decreases.

b. Decrease in Coil's Magnetic Field Strength in Article. The test coil magnetic field strength decreases through the article. This decrease in field strength which is the result of the eddy currents within the test article is mostly caused by the article's opposing magnetic field.

c. Effect of Frequency on Depth of Penetration. When a coil is applied to an article, the depth of penetration will vary with the test coil's frequency. As the frequency is decreased, the depth of penetration increases. For deep penetration low frequencies must be used, conversely high frequencies will produce maximum eddy current density at the surface. It should be realized that for a given article, changing the frequency changes the testing depth in that article. Table 2-1 illustrates how the depth of penetration varies with frequency for various materials.

d. Effect of Conductivity on Penetration. The depth of eddy current penetration is related to the conductivity of the article. As the conductivity increases, the depth of penetration decreases. It should be noted that with a given test frequency, the depth of penetration will change as the conductivity of the article changes.

e. Effect of Permeability on Penetration. When the article is a magnetic material, the effect of permeability on the depth of penetration must be considered. The depth of penetration decreases as the permeability increases.

Table 2-1. Typical Depth of Penetration

METAL	CONDUCTIVITY (% IACS)	RESISTIVITY MICROHM-CM	PERMEABILITY	37% DEPTH OF PENETRATION IN INCHES AT VARIOUS FREQUENCIES					
				1KC	4KC	16KC	64KC	256KC	1MC
COPPER	100	1.7	1	.082	.041	.021	.010	.005	.0026
6061-T6 ALUMINUM	42	4.1	1	.126	.063	.032	.016	.008	.0040
7075-T6 ALUMINUM	32	5.3	1	.144	.072	.036	.018	.009	.0046
MAGNESIUM	37	4.6	1	.134	.067	.034	.017	.008	.0042
LEAD	7.8	22	1	.292	.146	.073	.037	.018	.0092
URANIUM	6.0	29	1	.334	.167	.084	.042	.021	.0106
ZIRCONIUM	3.4	50	1	.446	.223	.112	.056	.028	.0141
304 STAINLESS STEEL	2.5	70	1.02	.516	.258	.129	.065	.032	.0164
HIGH ALLOY STEEL WITHOUT SATURATION*	2.9	60	750	.019	.0095	.0048	.0024	.0012	.0006
CAST STEEL WITHOUT SATURATION*	10.7	16	175	.018	.0089	.0044	.0022	.0011	.0006

*IF FERROMAGNETIC STEELS ARE TESTED USING SATURATION, THE DEPTH OF PENETRATION IS INCREASED TO APPROXIMATELY THAT NORMALLY FOUND IN STAINLESS STEEL.

203 TEST COIL INFORMATION CHARACTERISTICS

1. GENERAL

In eddy current testing all information about the article is obtained through the test coil. The characteristics of the coil, therefore, become a key factor in understanding what information can be obtained from the test article and reflected in an output indication. As shown in Figure 2-34, the basic electrical values of the eddy current testing system are the generator's output voltage (V), the current (I) flowing through the coil, and the coil's impedance (Z). The coil produces changes which can be defined as impedance changes or phase changes.

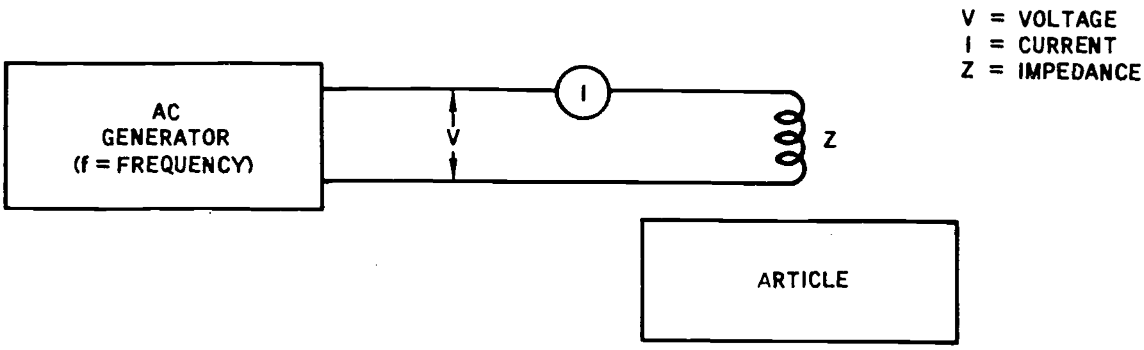


Figure 2-34. Eddy Current Testing System Electrical Values

2. ELECTROMAGNETIC WAVE

The velocity of electromagnetic waves in air is much greater than in the test article. The slow wave in the article takes a relatively long time to travel to a given depth and return the required information to the test coil. The velocity of the electromagnetic wave in a conductor is expressed by the following formula:

V = phase velocity

f = frequency

σ = conductivity

μ = permeability

$$V = \sqrt{\frac{4\pi f}{6\mu}}$$

For example, the velocity of the wave in copper at a frequency of 100 cycles is 12 feet/second, at 10,000 cycles it is 120 feet/second, and 1 megacycle it is 1,200 feet/second.

3. IMPEDANCE CHANGES

A coil is said to have a characteristic called impedance and the impedance value will change as the article's properties change. This provides the basis for a type of testing which is called impedance testing.

a. Definition of Impedance. Impedance is defined as the coil's opposition to the flow of an alternating current. The letter Z is used to denote this impedance. It is necessary to realize that impedance is not the same as resistance (R). A straight piece of wire has a resistance (R). And such a resistance will oppose the flow of an electrical current. This is true for either a direct current or an alternating current. When the wire is formed into a coil, the wire will offer more opposition to the flow of an alternating current (there is no change for a flow of a direct current).

This new opposition to the flow of an alternating current is called impedance. The coil's resistance is still present and is included in this impedance.

b. Effect of Impedance Changes on Current. The specific amount of current flowing through the coil is determined by the coil's impedance (Z). If this impedance changes, the current will change. An increase in impedance, decreases the current.

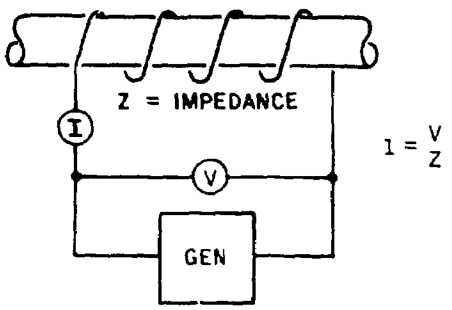


Figure 2-35. Impedance

Figure 2-35 shows that when an alternating voltage (V) from the generator is applied across a coil, an alternating current (I) will flow through the coil. The coil's opposition to this current flow is called impedance (Z). Knowing the value of Z and voltage (V), the actual current value could be calculated by the formula ($I = V/Z$).

c. Effect of Article Changes on Impedance. Since the coil's magnetic field affects the coil's impedance, a change in the field will change the impedance. The coil's magnetic field is changed by the field developed by the flow of eddy currents, this means that the article's properties will, through the eddy currents, change the coil's impedance.

In Figure 2-36, two sets of coils are being used and the test article is compared against a standard reference specimen. The secondary coils (S_1 and S_2) are connected together in such a way that the output of one coil opposes the output of the other coil. If the test article's properties are the same as the standard reference specimen's properties, no output voltage is developed. On the other hand, if the properties are not the same, an output is obtained. This output is related to the impedance of the coils. If the test article's properties change, the impedance will change.

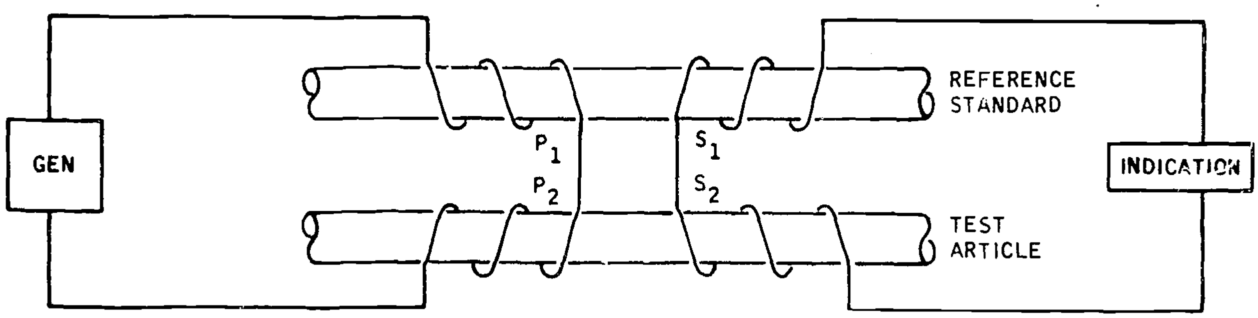


Figure 2-36. Comparison of Test Article to Standard Reference Specimen

d. Effect of Coupling Changes on Impedance. A coil's magnetic field extends outward from the coil as shown in Figure 2-37. Thus the intensity at point C is less than at point B; and point B's intensity is less than point A's.

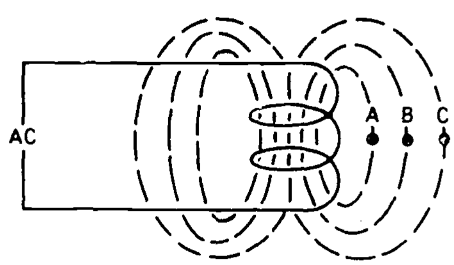


Figure 2-37. Coil's Magnetic Field

Because of this, the distance between the coil and the test article is a significant factor. If the distance varies, the output indication varies. This is true for two conditions:

(1) When the coil is placed above the test article (Lift-off), and

(2) When the test article is placed inside the coil (Fill Factor)

e. Effect of Frequency on Impedance. The alternating current generator provides an alternating voltage at a specific frequency (f). This voltage causes the flow of an alternating current. The generator's frequency is also related to the coil's impedance.

To determine the coil's impedance, two things are needed: (1) the electrical values of the coil and (2) the frequency applied to the coil. The coil's specific impedance depends upon the frequency applied to the coil and this impedance will change as the frequency is changed. Increasing the frequency will increase the impedance.

4. PHASE CHANGES

The test coil's characteristics not only change the amount of current (I) flowing through the test coil but also changes the phase relationship between the current through the coil and the voltage (V) across the coil. This relationship can be used to separate the variables appearing in the test coil as a result of changes in the article's properties.

a. Definition of Phase. As shown in Figure 2-38, the generator provides an alternating output voltage (V) which will have a definite frequency. This voltage will cause an alternating current to flow through a circuit connected to the generator.

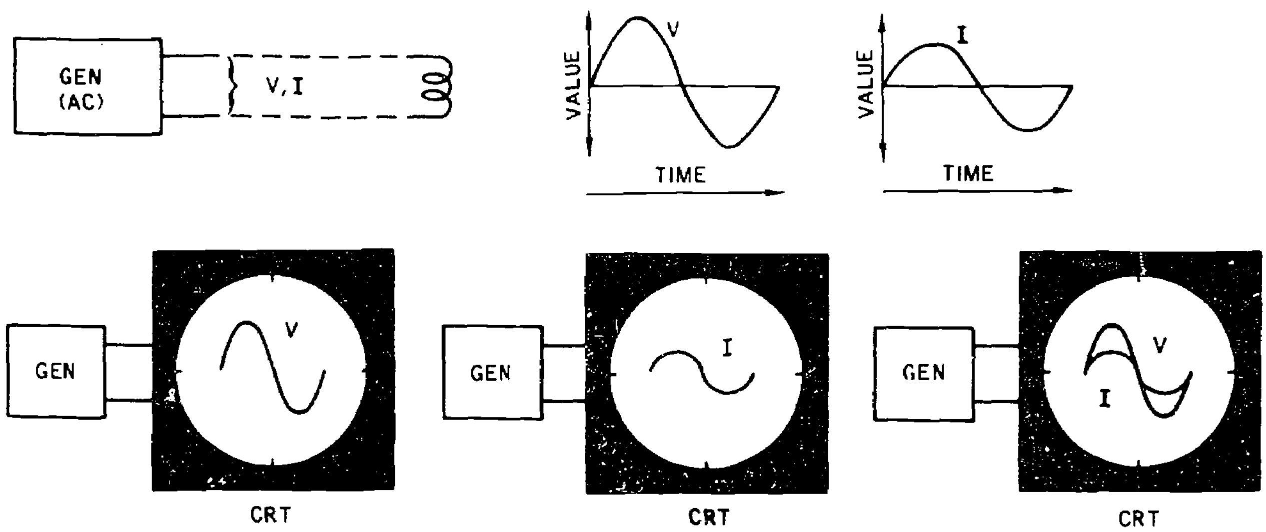


Figure 2-38. Alternating Output Voltage

(1) Figure 2-39 illustrates that the current flowing through an external circuit will be in phase with the voltage applied to the circuit when the circuit contains only resistance (resistor). The current (I) will rise and fall in step with the voltage (V). Under this condition, the current is said to be in phase with the voltage.

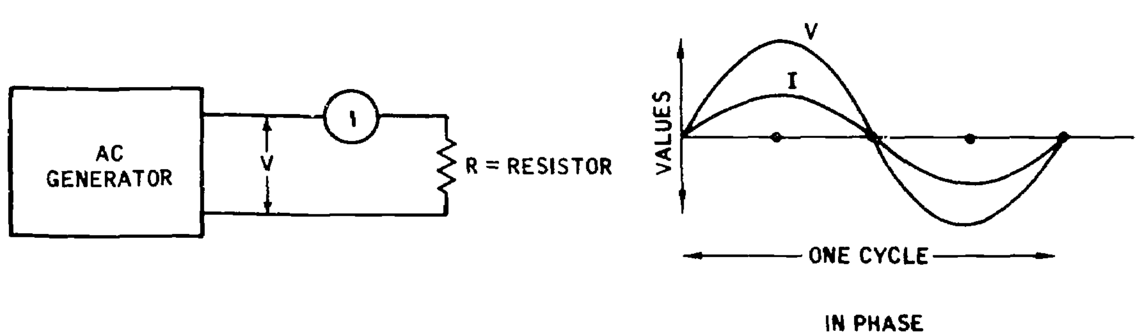


Figure 2-39. In Phase

(2) Figure 2-40 illustrates the condition where the current (I) is not in phase with the voltage (V). The horizontal scale represents time expressed in terms of a circle with 360 degrees. Since the current (I) is increasing at a time that is later than the increase in voltage (V), it can be said that the current lags the voltage. This current lag is caused by the coil's characteristics.

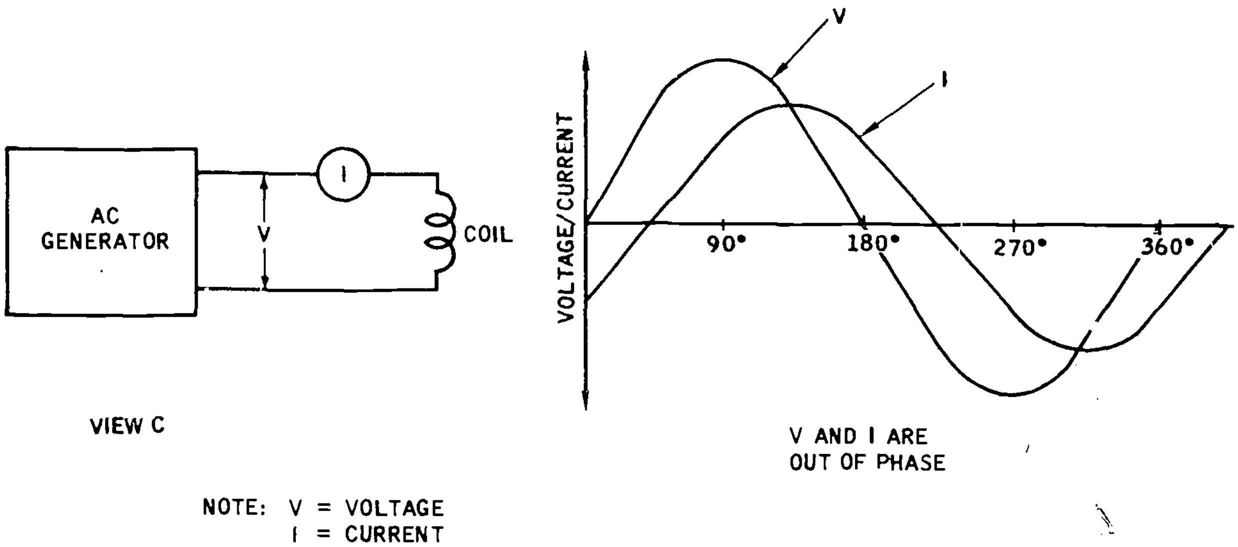


Figure 2-40. Out of Phase

b. Current/Voltage Phase Relationship. The phase relationship between the coil's current and the voltage applied to the coil changes as the coil's impedance changes. Since impedance changes are caused by variations within the article and by the coupling between the coil and the article, a basis exists for detecting variations by observing phase changes. This can be displayed with a cathode ray tube.

c. Definition of Inductance. Inductance is the resistance in a coil to the flow of an alternating current. When an alternating current flows around individual turns of a coil the associated magnetic field will induce a current in adjacent turns which flows in the opposite direction to the initial current (Lenz Law). Unlike a regular resistor, it only slows down the current flow, it does not reduce it. Thus, the lagging of current behind the voltage in a coil. Inductance is a magnetic property; resistance is not. A straight piece of wire has resistance, which still exists when the wire is formed into a coil. Inductance, on the other hand, only exists when the wire is formed into a coil. Under this condition, a magnetic field is established and is related to the coil's inductance. The article through the coil's field affects this inductance. Inductance (L) is that particular property of the coil which is determined by the number of turns, the spacing between turns, coil diameter, kind of material, type of coil winding, and the overall shape of the coil. Each coil has a unique value of inductance (L).

d. Coil's Magnetic Field Related to Inductance. A coil's inductance is caused by the magnetic field developed around the coil. This field (Figure 2-41) opposes a current change and causes the current to lag the voltage.

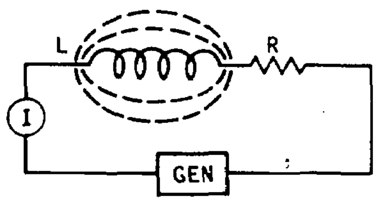


Figure 2-41. Inductance Caused by Magnetic Field

e. Definition of Inductive Reactance. The coil's opposition to the flow of current caused by the coil's inductance is a composite term which is referred to as the coil's inductive reactance (Figure 2-42). The symbol X_L is used to denote this term.

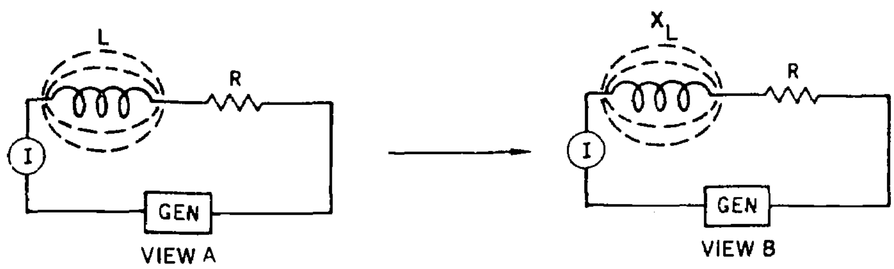


Figure 2-42. Coil Inductance/Inductive Reactance

In eddy current testing, we are not directly interested in the coil's inductance. What we are interested in is the inductive reactance (X_L). This is the coil's oppostion to current flow based on the coil's inductance and is determined by the coil's inductance and the frequency applied to the coil. $X_L = 6.28fL$; where f = the frequency of the alternating current applied to the coil and L = the coil's inductance.

The inductive reactance is therefore determined by the frequency as well as by the coil's inductance. Since the test frequency can be changed for a specific test application, it is important to recognize that test frequency as well as the article can change the inductive reactance.

f. Impedance/Inductive Reactance Relationship. Impedance is the total opposition to the flow of an alternating current and is composed of two values: the coil's resistance (R) and the coil's inductive reactance (X_L). Because of the voltage relationships of these two values, you can represent the two values in a graph and show that they are 90 degrees apart. The actual impedance of a circuit is some combination of these two values.

$$Z = \sqrt{X_L^2 + R^2}$$

Figure 2-43. Impedance/Inductive Reactance

To calculate impedance, use the formula shown in Figure 2-43, which is based on the relationships of the sides of a right triangle.

Another way is to locate the given value of the inductive reactance on the vertical scale of a graph as illustrated in Figure 2-43, and the given value of the resistance on the horizontal scale. The value on the vertical scale is then extended to the right while the value on the horizontal scale is extended upwards. The intersection of the two extensions gives a point. A line drawn from this point to the start of the vertical and horizontal scales (point O) gives the actual value of the impedance.

g. Inductive Reactance/Resistance Phase Relationship. A coil's characteristics can be divided into inductive reactance effects and resistance effects. As shown in Figure 2-44, the coil's current flows through both the coil's inductive reactance and the coil's resistance. The current is thus common to both values.

(1) When current flows through a resistance (R), a voltage exists across the resistance. This voltage is identified as V_2 in Figure 2-44. The same principle applies to the coil's inductive reactance and this voltage is denoted as V_1. The specific value of the voltage is the product of the current (I) and the resistance (R) or inductive reactance (X_L). Thus V_1 = IR and V_2 = IX_L.

(2) The voltage across the inductive reactance (V_1) is 90 degrees out of phase with the voltage (V_2) across the resistance. These two voltages can be represented in a graph (voltage plane) as shown in Figure 2-44. It is also possible to speak in terms of an impedance plane since the current is common to both the resistance and the

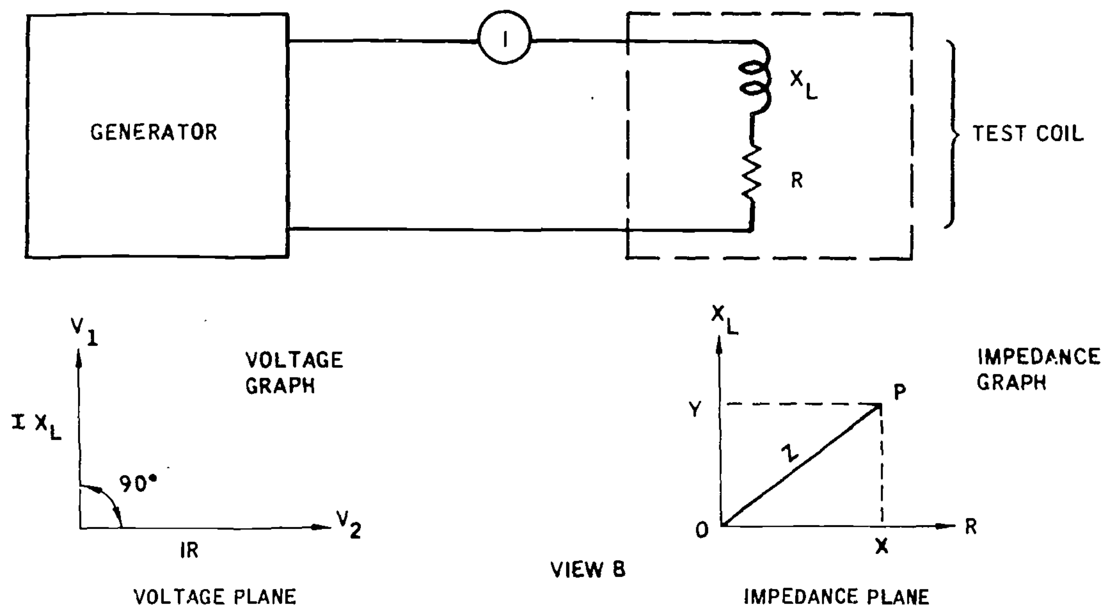


Figure 2-44. Coil's Impedance and Voltage Planes

inductive reactance. Because of the voltage relationship between these two values, it is possible to show these two values 90 degrees apart.

h. Phase Relationship in Secondary Coil. The out of phase condition between the current (I) and the voltage (V) also exists in the secondary coil of an eddy current testing system. In Figure 2-45, the generator causes an alternating current to flow through the primary coil and this develops a magnetic field which induces eddy currents in the article. The field also affects the secondary coil and induces currents in the secondary coil.

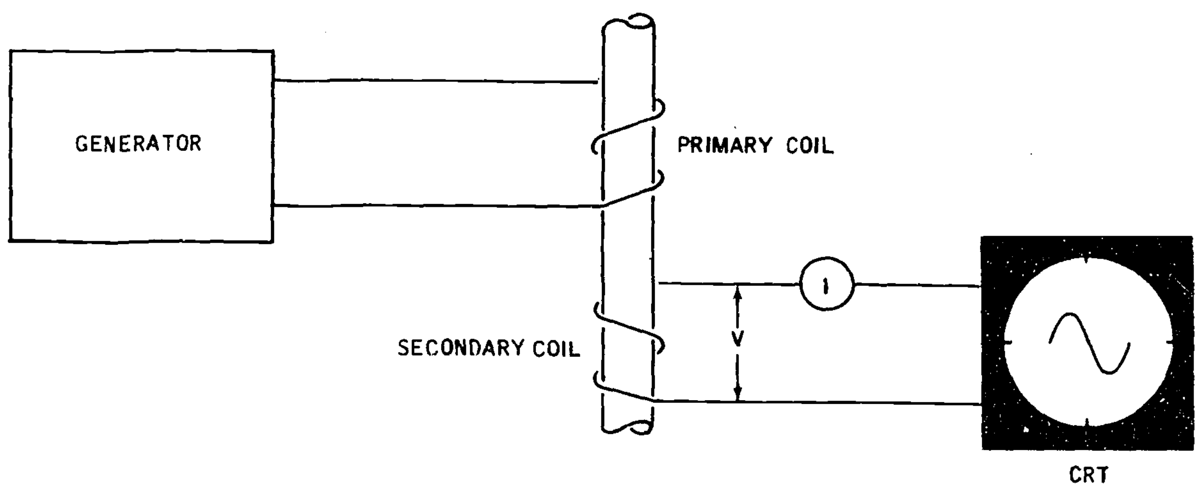


Figure 2-45. Current/Voltage Relationship in Secondary Coil

(1) The flow of eddy currents generates a magnetic field which affects the magnetic field developed in the secondary coil by the primary coil. The amount of current flow in the secondary coil, therefore, is determined by the eddy currents as well as by the primary coil.

(2) The voltage output of the secondary coil is not in phase with the current flowing through the coil. Moreover, the phase relationship between the current and the voltage will change as the secondary coil's impedance is changed by the article's properties.

(3) Through the use of a cathode ray tube, the shift in phase in the secondary coil can be seen. This factor is used in the eddy current phase analysis testing method.

(4) Like the primary coil, the characteristics of the secondary coil can be divided into resistance effects and inductive reactance. The voltage across the inductive reactance is 90 degrees out of phase with the voltage across the resistance.

i. Voltage Output of Secondary Coil. As shown in Figure 2-46, the secondary coil's output voltage is a composite value made up of the voltage across the inductive reactance (V_1) and the voltage across the coil's resistance (V_2). This composite voltage value (V_3) will lead the current through the coil by some phase angle. The phase angle will change as the coil is affected by the article.

j. Voltage Output of External Comparison Arrangement. The description above of the voltage output of a secondary coil can also be applied to a method using an external comparison arrangement as shown in Figure 2-47. In this case, the secondary coils are connected so that the output of one coil opposes and cancels the output from the other coil. If all conditions are equal, no output voltage will exist. On the other hand, if the conditions are not the same, an output voltage will exist and will be a composite value of the voltage across the inductive reactance and the voltage across the resistance. Since the voltage is an alternating voltage, an alternating waveform will appear on the cathode ray tube. This voltage will lead the current flowing through the secondary coils and the phase angle will change as the article's properties change.

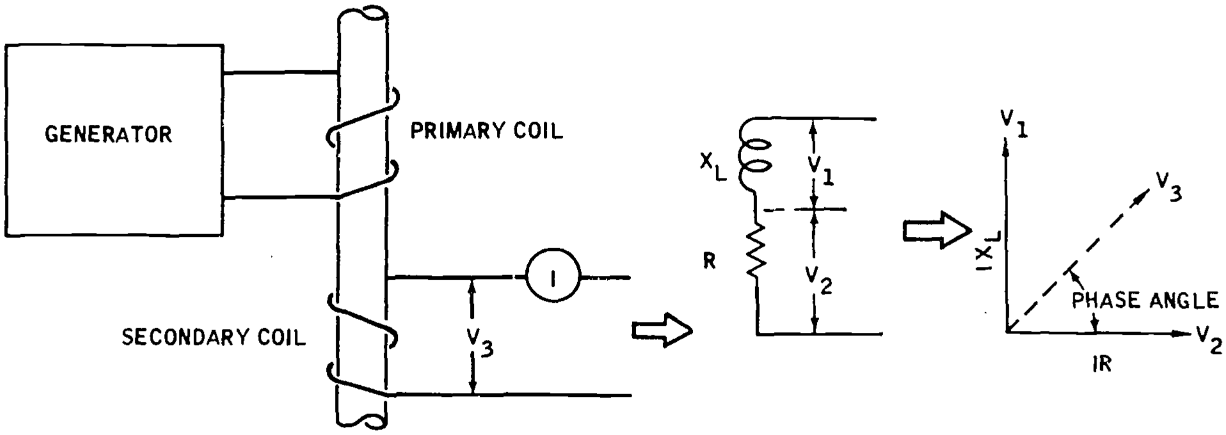


Figure 2-46. Voltage Relationship in Coil

204 PHASE CHANGES PRODUCED BY ARTICLE

1. GENERAL

An article's properties are being reflected in the test coil through the coil's impedance. A change in impedance denotes a change in the article's properties. The main problem in eddy current testing is to separate the article variables that are being reflected in the coil's impedance. The three main variables are conductivity, permeability, and dimensional changes. The dimensional changes change the coupling between the coil and the article.

2. CONDUCTIVITY, PERMEABILITY, AND DIMENSION VARIABLES

Using the test system shown in Figure 2-47, it can be demonstrated that each of the three main variables can produce a phase change. Eddy current testing based on the use of these phase changes is called phase analysis.

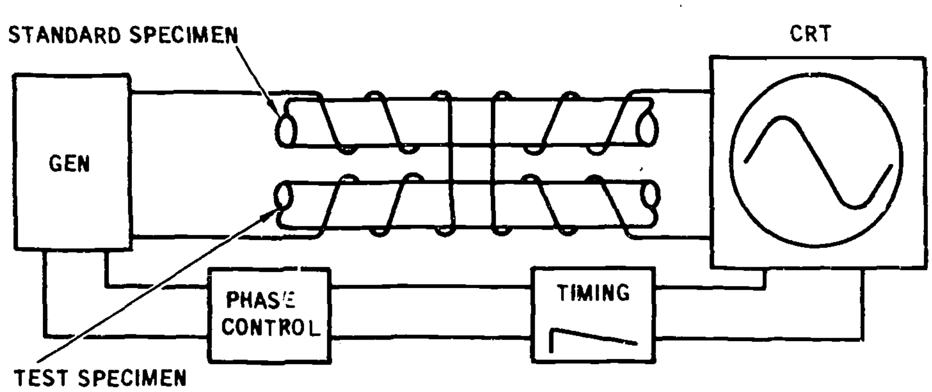


Figure 2-47. Voltage Output of External Comparison Arrangement

3. CONDUCTIVITY PHASE CHANGES

To illustrate how changes in conductivity can produce phase changes, we can use the test system in Figure 2-47. If a test article which has properties that are the same as those of the Reference Standard used in the test system, no output voltage will be obtained. If the test article is now replaced by one that has a slightly different conductivity, an output voltage will be obtained and the waveform can be observed on the cathode ray tube. If this second test article is replaced by another article with a different conductivity, it can be observed that the waveform on the cathode ray tube will shift phase. Using a series of such articles, the direction of this phase change can be defined. Figure 2-48 illustrates the direction of phase change produced by the conductivity variable. The symbol (σ), pronounced sigma, is used to define the conductivity variable.

4. PERMEABILITY AND DIMENSION PHASE CHANGES

If the technique used to detect conductivity phase changes is applied to each of the two remaining variables, permeability and dimension, the two variables will produce phase changes in the same direction. This condition is illustrated in Figure 2-48.

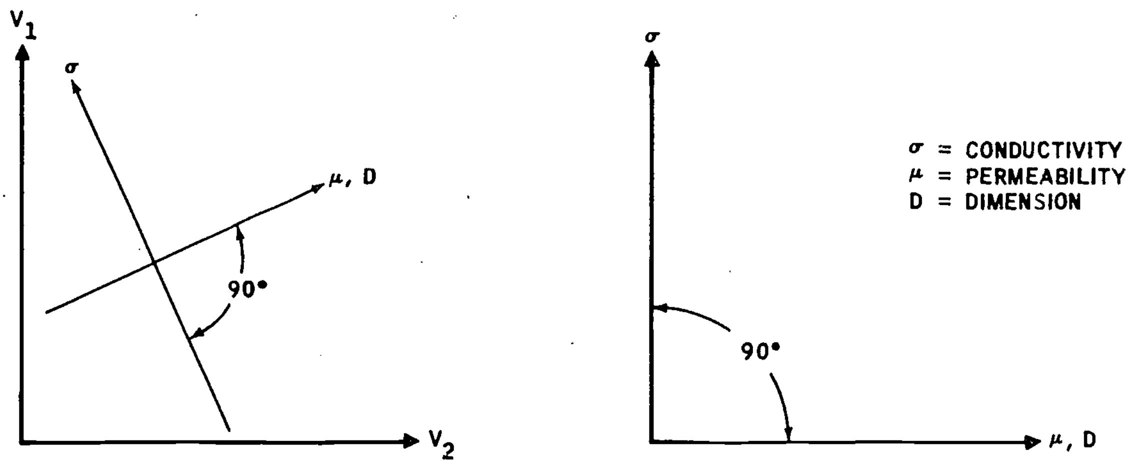


Figure 2-48. Conductivity, Permeability, and Dimension Phase Changes

5. RELATIONSHIP BETWEEN ARTICLE PHASE CHANGES

Separation of the variables reflected in the coil's impedance by the article's properties is possible because the direction of phase change for the conductivity variable is not the same as the direction of phase change for the permeability and dimension variables.

a. Two Directions Are 90 Degrees Out of Phase. In Figure 2-48 the directions of phase change are 90 degrees out of phase. This provides the basis for saying that the article's conductivity variable is perpendicular or 90 degrees out of phase with the article's permeability and dimension variables.

b. Qualifications. When the statement is made that the conductivity variable is perpendicular to the permeability and dimension variable, it is important to realize that this is only true under certain test conditions. Normally these conditions are established when it is desirable to separate the variables.

(1) Figure 2-49 illustrates a family of curves obtained by holding all variables but one constant and letting the one remaining variable change over a range of values. For example, curve A was developed by holding the permeability and dimension variables constant and letting the conductivity change. The result is a plot of discrete values that form the curve. A change from point X to Y represents an increase in conductivity. The reader should realize that point X is the output voltage which is a composite of voltages V_1 and V_2 and forms a phase angle as defined in Figure 2-46. When the conductivity changes to point Y, this phase angle changes to a new value. Thus it can be seen that the curve represents a direction of phase change.

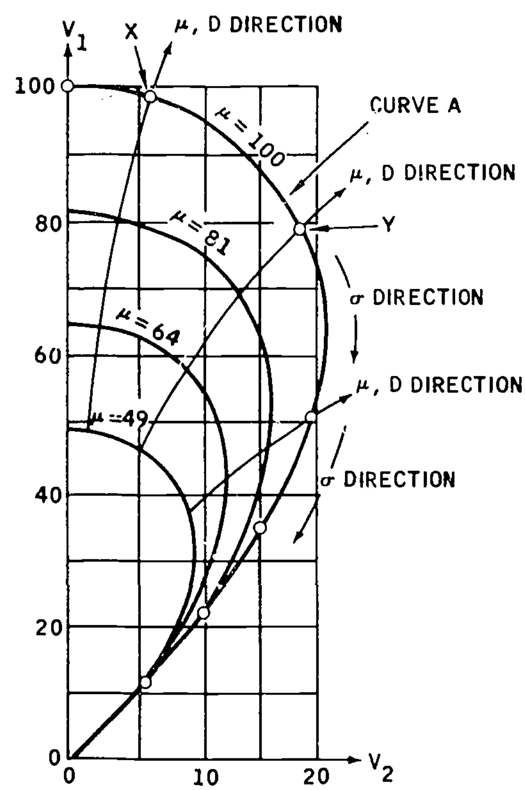


Figure 2-49. Family of Curves Showing Variability Within Magnetic Article

(2) If the conductivity is held constant and the permeability is allowed to vary, a set of voltage values is again obtained. The plot of this set of values will be approximately perpendicular to the curves covering conductivity.

(3) Figure 2-49 shows that the variables are not always perpendicular. Points X and Y represent perpendicular points. Through the proper selection of a test frequency, point X or Y can be selected for the test situation; therefore, the phases can be said to be perpendicular. For other points of operation, this will not be true.

(4) Figure 2-50 shows both conductivity and permeability superimposed on the same curve. It is readily seen that permeability is not only in an opposite direction than conductivity, but many times greater. This fact means any permeability present will mask out conductivity effects.

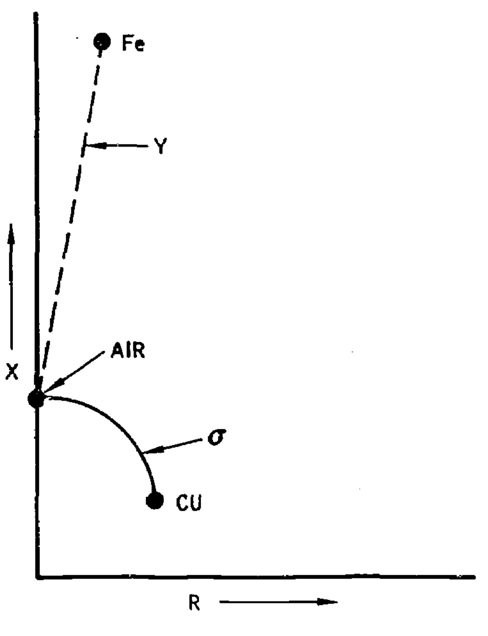


Figure 2-50. Conductivity/Permeability

c. Importance of Phase Direction Difference. The conductivity variable produces a phase change that is perpendicular to the permeability, and dimension variables can be used to separate this variable from the other variables in the eddy current output indication. This technique will be defined under the phase analysis testing treatment in Chapter 3.

CHAPTER 3: EDDY CURRENT EQUIPMENT REQUIREMENTS
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CHAPTER 3: EDDY CURRENT EQUIPMENT REQUIREMENTS

300 GENERAL

A breakdown of the eddy current testing system shows that it is composed of various key systems which are an integral part of the electromagnetic testing task. This chapter will review these systems analyzing the type of equipment which is required to support that system. It will show how the various items within each system have specific capabilities and how these capabilities can be used in the over-all task of eddy current testing.

In eddy current testing, more so than in any other method of nondestructive testing, the testing system is designed to fulfill a particular need. The testing parameters which dictate the choice of one system over another are just as important as the test system itself. In making an analysis as to the system to be used the NDT Specialist must first determine the status of many questions, some of which are:

a. Type of material; is it magnetic or nonmagnetic?

b. Type of problem; discontinuities, alloy composition, cold working, over aging, etc.

c. How these properties affect the article; will there be a conductivity change in nonmagnetic materials, or a conductivity and/or permeability change for ferromagnetic materials.

The validity of the eddy current test rests solely on the capability of the NDT Specialist to determine which system (equipment) would be required to resolve the specific problem (task).

301 SENSING SYSTEM

1. GENERAL

The key element of the eddy current sensing system is the test coil. Since the article configuration comes in many shapes and sizes, the coils likewise assume these configurations.

2. TEST COIL ARRANGEMENTS

Test coils can be arranged in a number of ways. They may be placed around the article, inside the article or on the surface of the article. In each case the coil can be a single winding or a double winding arrangement. Generally, the second coil (secondary) is wound inside the primary coil. Physically, the coil appears as one single coil. Another type of double wind is the split coil or differential coil. These types of coils are wound side by side. Coils are wound on non-conducting materials, e.g., plastic, phenolic, etc.

a. Surface Coil Arrangement. A surface coil (Figure 3-1) is designed for use on the article surface. For maximum effect, this coil must fit the contour of the surface. The coil can be contacting or non-contacting, operator held or automated.

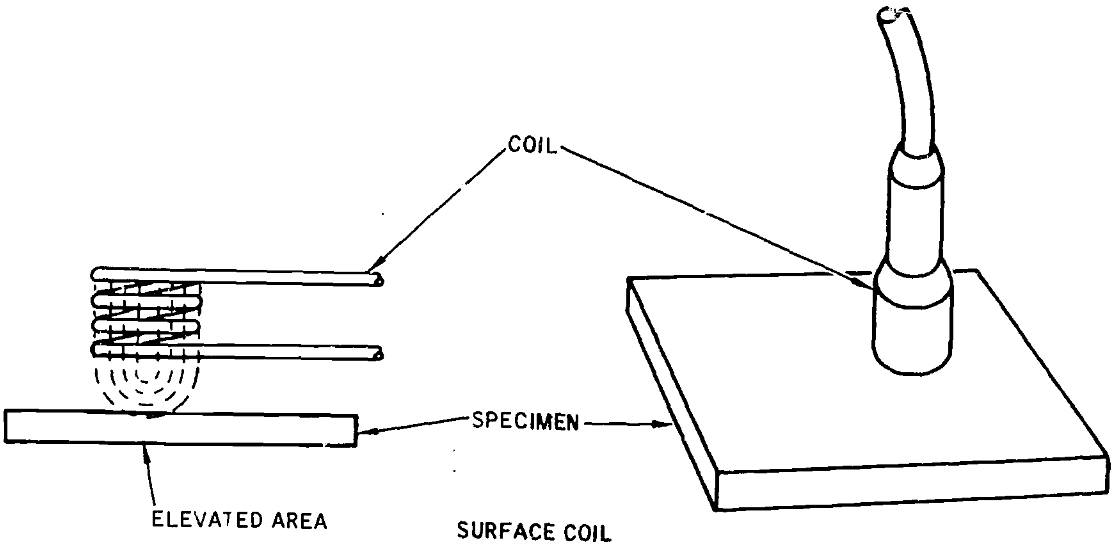


Figure 3-1. Surface Coil

(1) Gap Coil. Although from external appearance it is not always apparent, the probe may be shielded as shown in Figure 3-2.

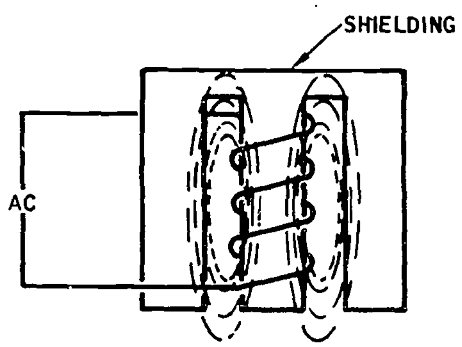


Figure 3-2. Shielded Gap Coil

(2) Spring-Loaded Coil. To minimize lift-off effects, spring-loaded coils (Figure 3-3) are often used. This ensures that the coil maintains constant contact with the article's surface and that this contact has a constant pressure. Such coils can also be designed to hold the coil a specific distance above the article's surface.

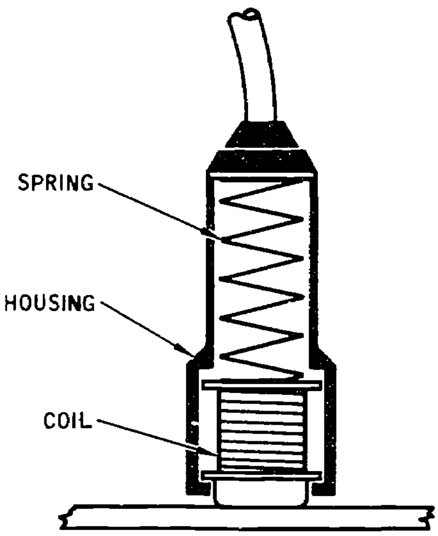


Figure 3-3. Spring-Loaded Surface Coil

(3) Spinning Coils. Figure 3-4 illustrates the use of a surface coil mounted so that the coil can be rotated about the circumference of the article. Oftentimes, both the encircling coil and the spinning coil are used to ensure complete coverage of the area of interest. It should be noted that the coil may be stationary and the work rotated and traversed.

b. Encircling Coil Arrangement. The encircling coil (Figure 3-5) is used to enclose an article about one of its axes to give the maximum effect from the article. This coil must be shorter than the article to reduce end-effect.

(1) Shape of Coils. The shape of the coil is not always circular. A coil produces the maximum effect if it closely coincides with the surface of the article being tested as in Figure 3-6.

c. Inside Coil Arrangement. The inside coil, Figure 3-7, is identical to the encircling coil but placed inside to maximize the sought after effects. To localize discontinuities within a tube, inside surface coils can be constructed with remote controls which permit the NDT Specialist to position the coil at specific spots on the inside circumference of the tubing.

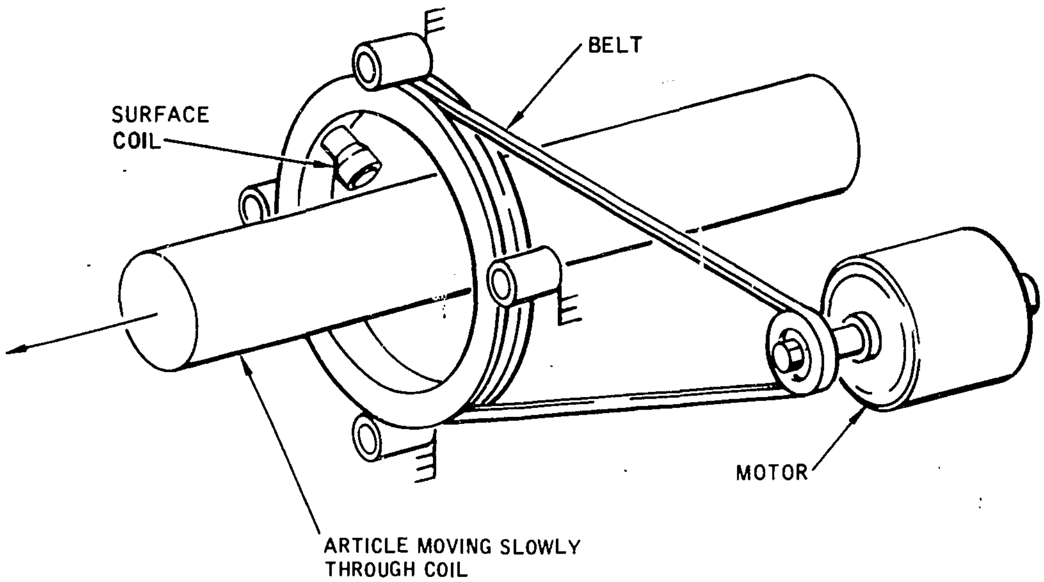


Figure 3-4. Example of Spinning Coil Arrangement

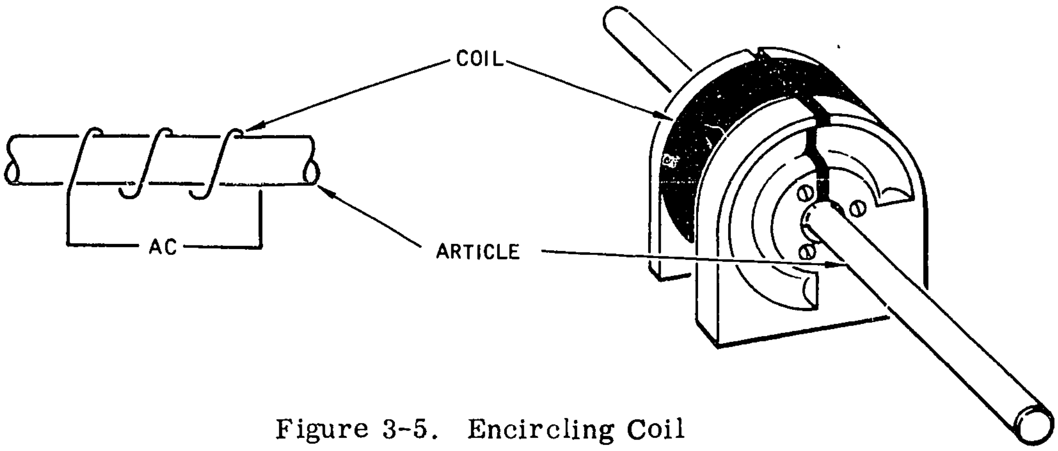


Figure 3-5. Encircling Coil

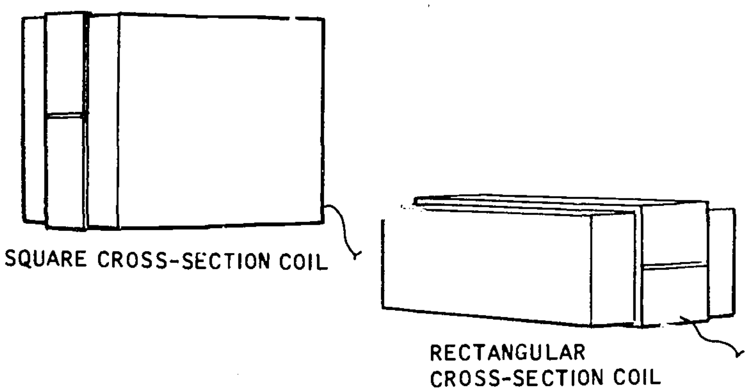


Figure 3-6. Noncircular Test Coils

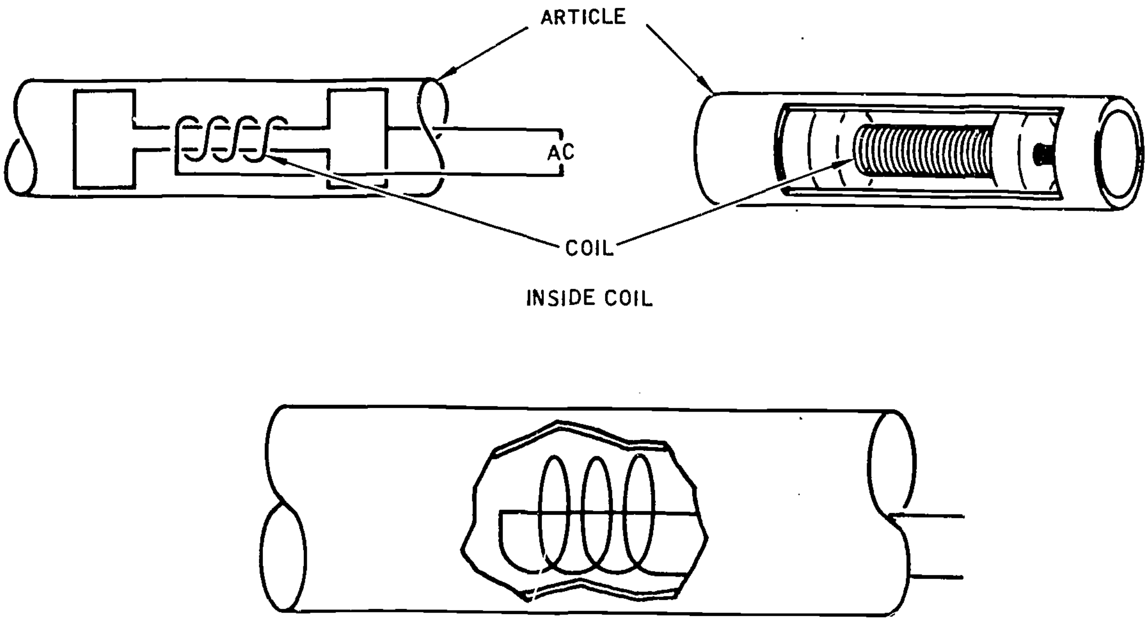


Figure 3-7. Inside Coil

d. Gap Probe. This is a test coil using magnetic material to purposely shape the magnetic field to enhance the article's effect on the induced eddy currents (similar to a recording head), Figure 3-8. The probes can be either single coil or differential coils. The gaps involved typically are 0.015" wide by 0.125" long, which allows very small defects to produce a sizeable indication. This probe may also be used to follow varying surfaces of the article, which tends to make it fairly universal for nonuniform shapes.

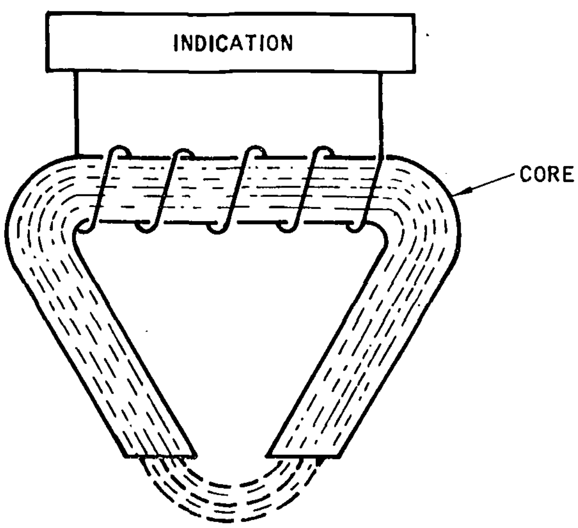


Figure 3-8. Gap Probe

e. Focused Coils. The focused coil's magnetic field is specially shaped or focused by the method of winding (Figure 3-9). When this type of coil is used, the relation and direction in which the article is presented to the coil must be consistent.

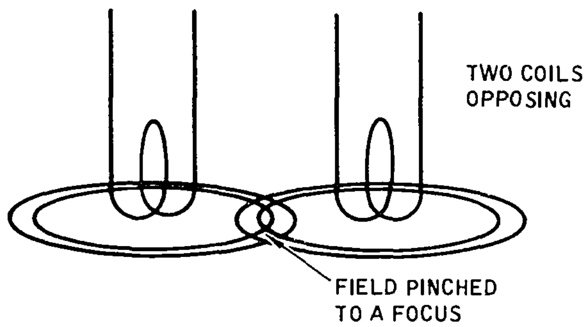


Figure 3-9. Focused Coils

f. Wide and Narrow Encircling Coils. The width of the coil is a function of the application. Wide coils cover large areas, so they respond mostly to bulk effects, e.g., conductivity; whereas, narrow coils sense small areas and will respond to lesser effects, e.g., discontinuities (Figure 3-10). It must also be remembered that the coil must be small enough to avoid end effects.

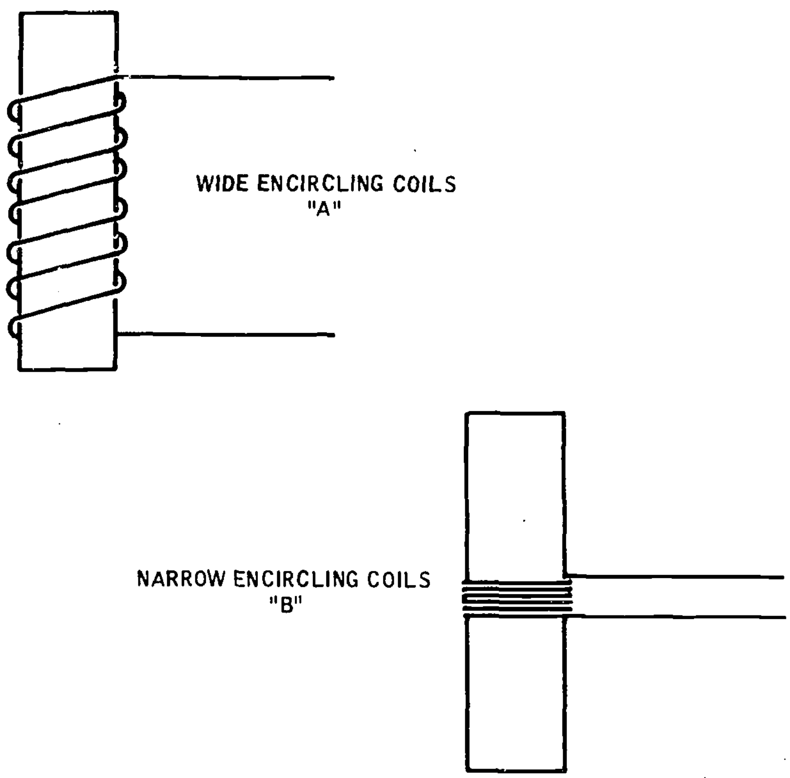


Figure 3-10. Wide and Narrow Encircling Coils

g. Direct Current Saturation Coils. Eddy current testing uses alternating current; however, when testing magnetic materials, a saturation technique suppresses the permeability. This saturation is accomplished by a direct current coil which surrounds the eddy current test coil to maintain domain alignment within the test article. Since this direct current magnetic field is stationary, there is no effect on the test coil. It can be seen that this direct current has to be free of ripple. This can be accomplished by winding the dc coil on a metal core. The larger the volume of the magnetic material within the test coil, the stronger the dc saturation field must be, usually requiring water cooling. The article tested may contain some residual magnetism after the test, which may be removed by demagnetizing.

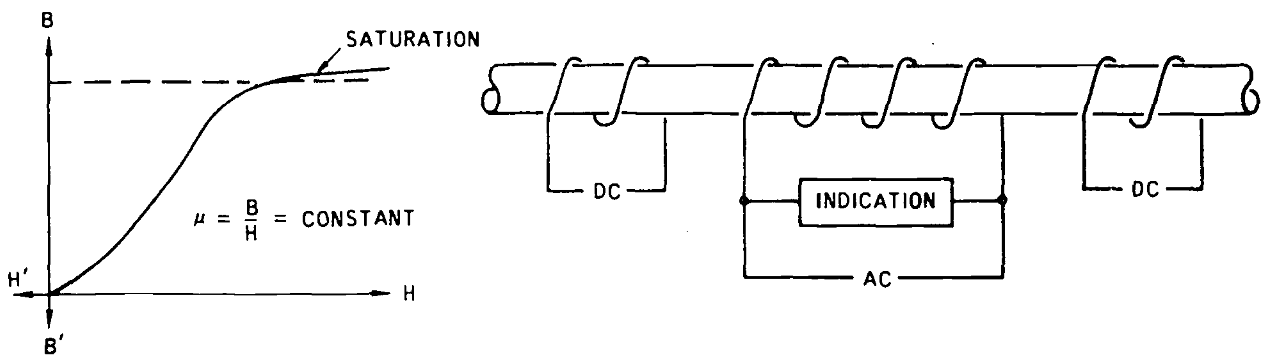


Figure 3-11. Direct Current Saturation Coil

Notice in Figure 3-11 that the magnetizing curve approaches a maximum point where further increases in H will not produce a change in B-H values. This means that further changes in magnetizing force (H) will not produce changes in flux density. When such a condition exists, the article is saturated. And under such a condition, the permeability is constant. One way to saturate the article is to use a direct current (dc). Note that a dc coil is positioned on each side of the ac coil used in the rod under test.

When an article is saturated, the magnetic properties of the article will not generate further flux changes. The remaining flux changes will be caused solely be the test coil.

3. SINGLE ABSOLUTE COIL ARRANGEMENT

Figure 3-12 illustrates the single absolute coil arrangement. In this arrangement, the same coil is used to induce eddy currents in the article and sense the article's reaction on the eddy currents. This environment can be used for all three classes: encircling coil, inside coil, and surface coil.

This single coil will test only the area under the coil and does not compare itself with a reference standard (external reference). Because it tests the article without a comparison, we call it "absolute."

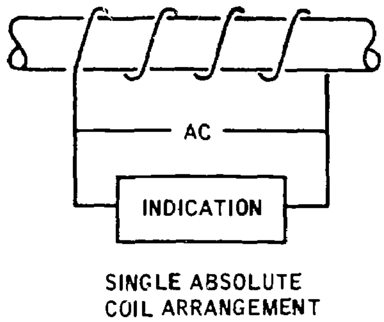


Figure 3-12. Single Absolute Coil Arrangements

4. DOUBLE COIL

It is also possible to use two coils; one to establish the magnetic field and induce eddy currents into the article, and one to detect the changes in eddy current flow (Figure 3-13). Note that this secondary coil has the indicating device connected across the coil and is not connected to an ac source. Normally the secondary coil is located inside the primary coil and the two coils are referred to as a double coil.

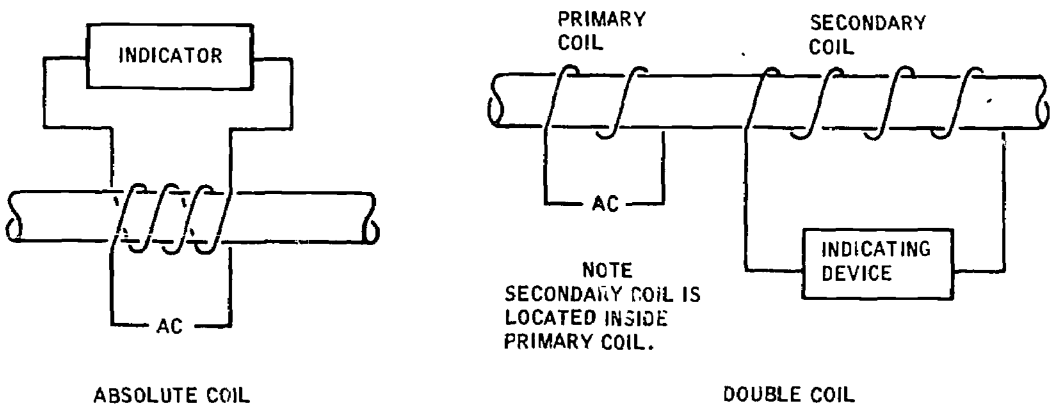


Figure 3-13. Double Coil (Absolute)

In the double coil arrangement, the primary coil induces eddy currents into the article. The eddy currents, in turn, generate a magnetic field that reacts against the primary coil and also induces a current in the secondary coil. The indicating device presents the changes in eddy current flow.

5. DIFFERENTIAL COIL ARRANGEMENT

The differential coil arrangement shown in Figure 3-14 provides a means of balancing out effects that are the same. The two coils are wound and connected so that the output of one coil cancels the output of the other coil when the article properties are the same under both coils. Only a slight difference (differential) in material properties causes an imbalanced output indication.

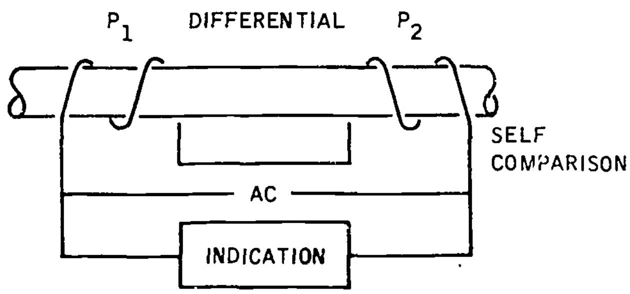


Figure 3-14. Differential Coil Arrangement

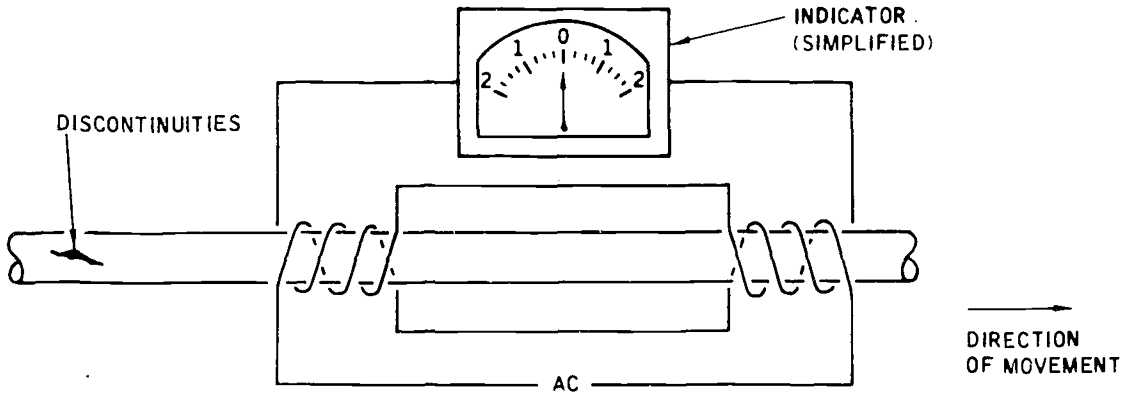
6. SELF-COMPARISON ARRANGEMENT

Figure 3-15 illustrates the technique of self-comparison. This technique uses one area of the test article as a reference standard against which another area on the same article is compared. It is assumed that a discontinuity will not extend over both areas or that the discontinuity extending over both areas is oriented so that a difference will still be developed and reflected in the indication.

7. EXTERNAL COMPARISON ARRANGEMENT

The coil arrangement in Figure 3-16 is exactly the same as the self-comparison coil except that it is set up slightly different. A differential coil arrangement can be set up with a carefully chosen, discontinuity-free test reference held stationary in one coil while the article being tested is moving through the other coil.

Here, coils P2-S2 and the discontinuity-free article are set up as a reference standard. As the article being examined passes through coils P1-S1, a comparison is made with the reference standard. No indication is observed of course unless a discontinuity appears in the test article being examined. If a discontinuity passes through coils P1-S1, it causes a change in the coil impedance and thus an indication is exhibited.



Differential Coils

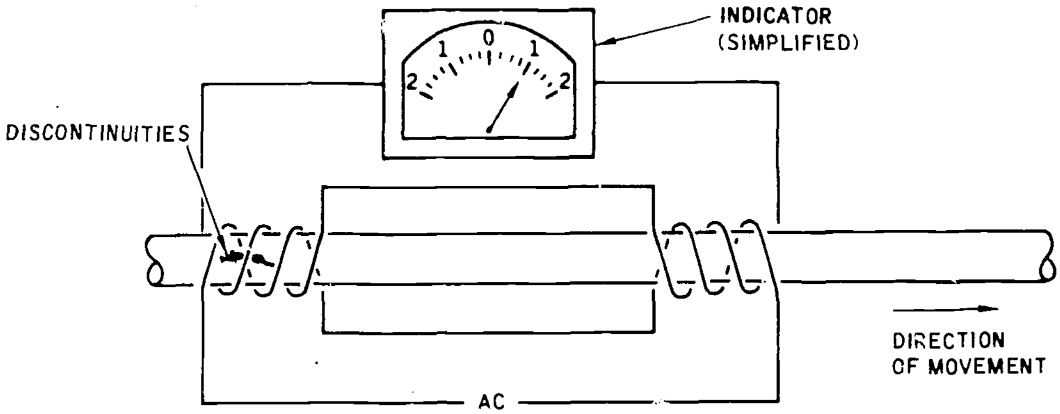


Figure 3-15. Self Comparison Coils

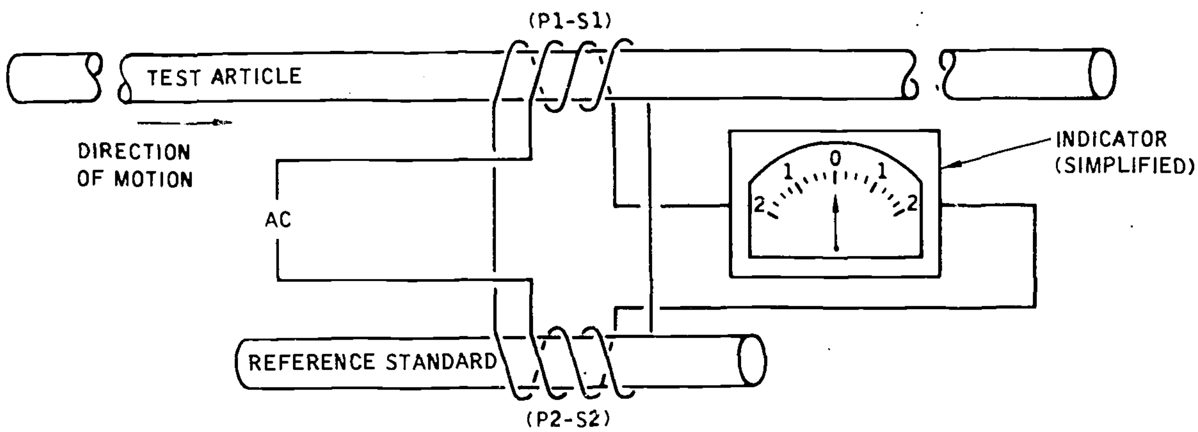


Figure 3-16. External Comparison Arrangement

302 IMPEDANCE TESTING SYSTEM

1. GENERAL

Eddy current testing can be divided into three broad areas. These are referred to as impedance testing, phase analysis testing, and modulation analysis testing. The following paragraphs will describe the impedance testing; subsequent paragraphs will cover the two other forms of testing.

2. DEFINITION OF IMPEDANCE TESTING

Testing based on a gross change in the impedance of the test coil when the test coil is placed near the article is called impedance testing. Figure 2-35 illustrates such a system. In this case, the value of the current is changed by the impedance and this change in the current value provides the basis for an output indication. Most of the portable conductivity testers and discontinuity detectors use circuits based on the gross change in impedance when the test coil is placed near the article.

3. TECHNIQUES

The testing technique is simple and direct when impedance testing is used. In most cases, the test coil is applied to the article and an observation is made. Normally, one assumes that certain factors are constant; thus, a change in indication can be assumed to be related to only one variable.

4. ADVANTAGE AND LIMITATIONS

The main advantage of impedance testing is the elimination of the need for extensive setup procedures. The technique is generally limited to static conditions, since a moving system would increase the number of variables appearing in the output indication. For example, in a moving encircling coil system the presence of dimension changes would make it impossible to separate the conductivity variable from the dimension change in the output indication when impedance testing is used.

303 PHASE ANALYSIS TESTING SYSTEM

1. GENERAL

The difference in phase between the current flowing through a test coil and the voltage appearing across the coil provides the basis for phase analysis testing.

2. DEFINITION OF PHASE ANALYSIS TESTING

Phase analysis testing is defined as testing that is based on phase changes that occur in the test coil, and the article affect on these phase changes. Through the cathode ray tube, these phase changes can be detected and used to make decisions about the article. It is also possible to establish conditions so that some variables which produce phase changes can be suppressed and only the variable of interest will be displayed.

3. TECHNIQUES

Phase analysis testing is identified by three basic methods: vector-point method, ellipse method, and linear time-base method. Each of these methods provides a means of separating the conductivity variable from the permeability and dimension variables. The permeability and dimension variables produce phase changes in the same direction; therefore, it is not possible to separate these two variables by phase analysis testing unless direct current saturation is used.

a. Vector-Point Method. Figure 3-17 illustrates the vector-point method. In this method the CRT display is a point of light which represents the composite voltage of the two voltages in a test coil. These two voltages are 90 degrees out of phase, and the composite voltage will be some combination of these two voltages. Through phase shifting circuits and frequency selection it is possible to have voltage V_1 be the effect caused by the dimension variable (assume the permeability is constant) and to have voltage V_2 be the effect caused by the conductivity variable. The point of light will represent some combination of the two effects.

(1) Through positioning controls it is possible to adjust the circuits so that the point of light will fall in one of the four 90-degree apart areas on the CRT screen. Figure 3-17 shows the point of light in the first 90-degree area. Under these conditions a movement in the OX direction (horizontal direction) will represent a conductivity change - view "A." Likewise, a movement in the OY direction (vertical direction) will represent a dimension and/or permeability change - view "B."

(2) When the properties of both articles are the same, no output voltage will be developed; thus the point of light will be centered on the CRT screen.

(3) The presence of a variable in the test article that is not the same as that of the reference standard will cause the point of light to move. By analyzing this movement (e.g., horizontal movement or vertical movement) it becomes possible to know which variable (conductivity or dimension) is causing the change. When both variables are affecting the output indication at the same time, it is also possible to observe the extent of the variable's effect on the output indication.

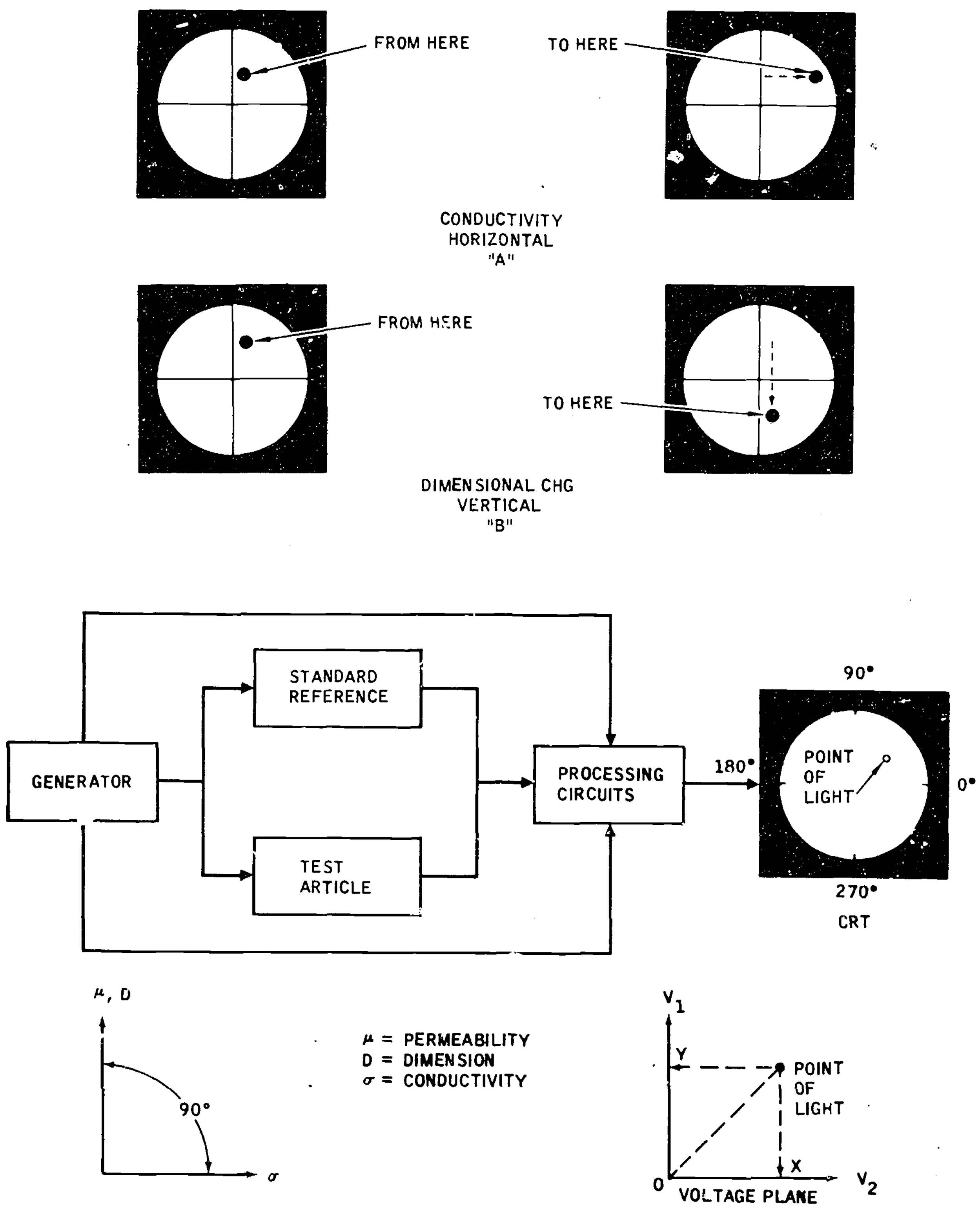


Figure 3-17. Vector-Point Method

b. Ellipse Method. Figure 3-18 shows in block form, the ellipse method. Like the vector-point method, two articles are used and the test article is balanced by the reference standard. Normal output is a straight horizontal line when a condition of balance exists.

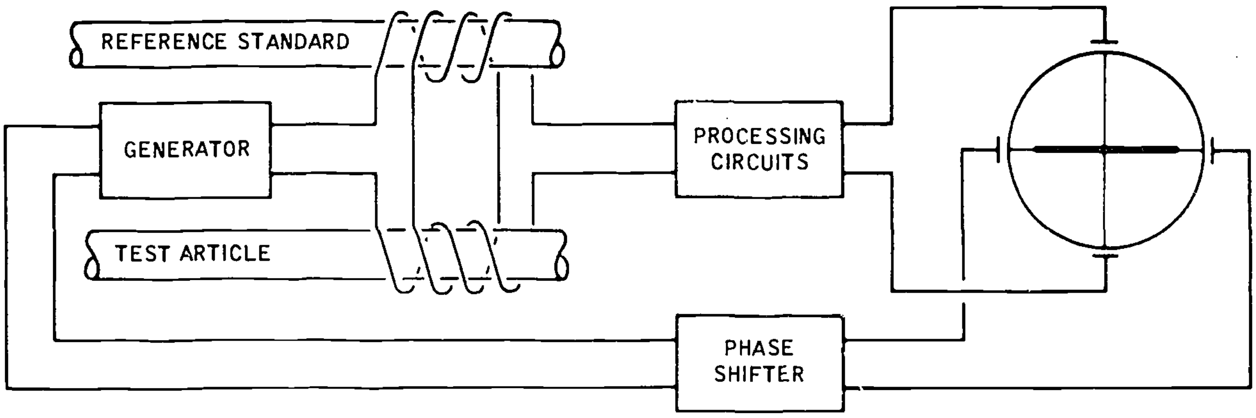


Figure 3-18. Ellipse Method

The phase shifter serves the same purpose for the ellipse method as it did for the vector-point method. It positions the display horizontally on the cathode ray tube.

(1) The ellipse method is capable of showing two variables at the same time. One variable is reflected by the position of the ellipse (or straight line) in the CRT; the other variable is indicated by the size of the ellipse opening (small loop or large loop).

(2) In the normal application under balanced conditions, the CRT display will be a horizontal straight line. This line will assume an angular orientation if a condition of unbalance arises (Figure 3-19). The significance of the change can be assigned to the conductivity variable or to the dimension variable, depending upon how the initial conditions are established.

(3) The size of the loop (Figure 3-19) provides the information about the second variable and this size can be related to the scales on the CRT screen to obtain quantitative values.

(4) When both variables (Figure 3-19) appear at the same time, an ellipse which is oriented at an angle will appear on the CRT. Through the use of the CRT screen scales, the two variables can be evaluated quantitatively.

(5) In a typical application, the orientation of the ellipse can represent the conductivity variable while the size of the loop can represent a dimension variable. It thus becomes possible to see both variables at the same time.

e. Linear Time-Base Method. The process of learning something about the article through a phase change is called phase analysis. There are several forms of phase analysis. In one, the linear time-base method, the timing voltage is the time base.

(1) Since the timing voltage moves the CRT dot across the screen at a steady rate, the voltage is called a linear voltage. The idea of time comes from the time required to move the dot across the CRT screen.

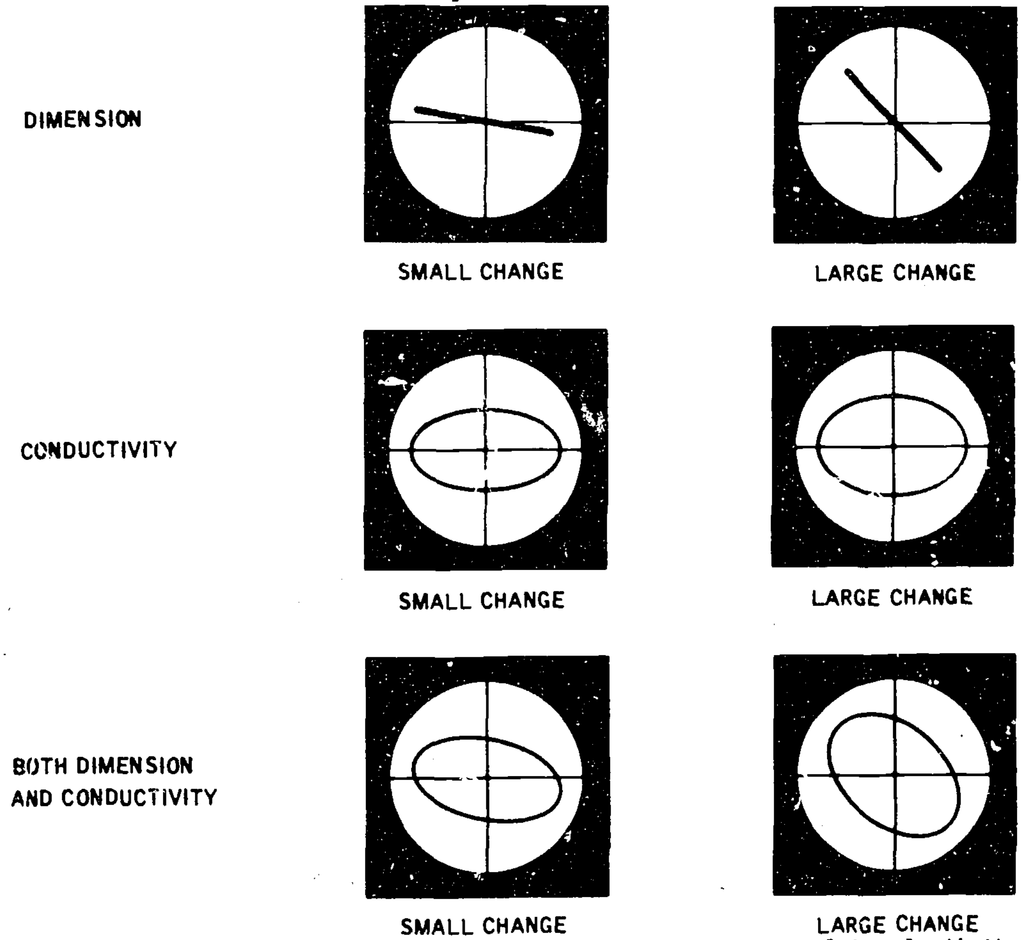


Figure 3-19. Cathode Ray Tube Displays for Dimension and Conductivity

This time is the period for one complete cycle and is the same period as the period of the voltage cycle applied to the CRT's vertical plates.

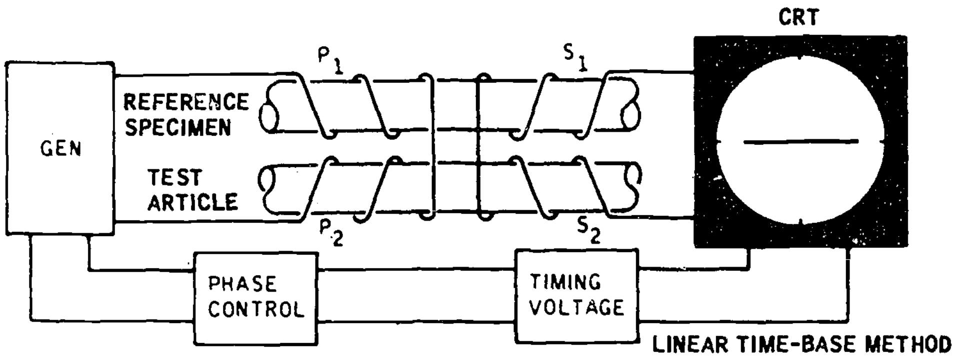


Figure 3-20. Linear Time-Base Method

(2) Figure 3-20 illustrates a typical linear time-base method using two sets of test coils. Notice that the secondary coils are connected together. Under this coil arrangement, the voltage developed by coil S_1 opposes the voltage developed by coil S_2. This means that no output voltage will be developed across the secondary coils S_1 and S_2 when the test article has properties identical to the properties of the standard article. For this case, the CRT display will be a straight horizontal line which is the timing voltage. No voltage will be applied to the vertical plates.

(3) The generator's output is an alternating voltage which has a definite frequency (number of cycles per second).

If one cycle of alternating voltage is applied to the CRT, a vertical line will appear on the screen. To get the dots to move across the screen, a second voltage is applied to the horizontal plates. This voltage will move the dots across the screen at a steady rate. The voltage is normally called a timing voltage and has a time period which is the same as the period of the alternating voltage applied to the vertical plates. A period is the time required to complete one cycle. Circuits within the CRT provide a means of blanking out the screen after one cycle so that the cycle can start again at the left side of the screen. In this way you can get a continuous picture of one waveform.

(4) One cycle of the generator's output appears as a waveform. Since this waveform is being constantly repeated and since the timing voltage is repeatedly sweeping across the CRT in time with this waveform, the result is a steady waveform on the CRT.

(5) The waveform shown in Figure 3-21 appears on the CRT because a condition of unbalance exists between the test article and the reference standard.

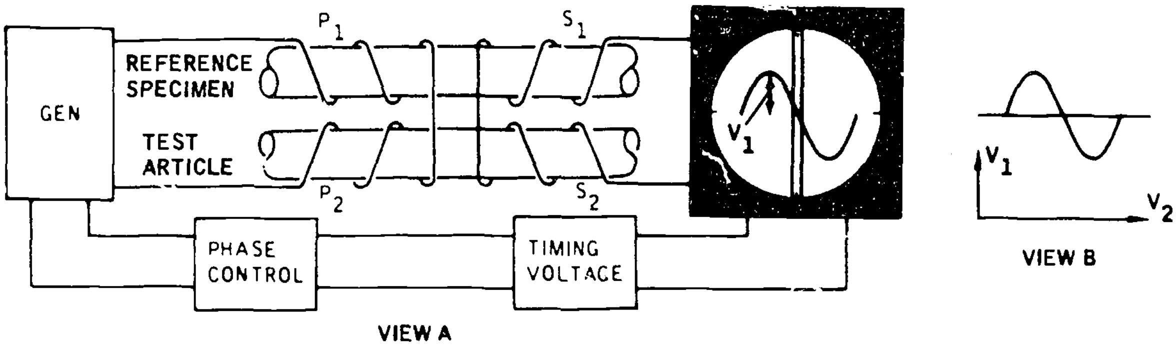


Figure 3-21. Unbalance Wave Form

The test article has the same permeability and conductivity properties as the reference standard. The only difference between the reference standard and a test article is a change in dimension. Under these conditions a waveform will appear on the CRT screen. The CRT display can be any of a number of different displays; however, by using the phase control the waveform is adjusted as shown in view A.

View B illustrates the voltage waveform applied to the CRT's vertical plates.

(6) As shown in Figure 3-22, the CRT display may assume a number of indications. The specific indication depends upon where the timing voltage starts the display of the generator output voltage. Any part of the generator waveform can be used as a starting point. This accounts for the number of displays shown.

(7) In the linear time-base method, a vertical transparent piece with a slit marked on it is used to assist the NDT specialist in evaluating the waveform display (Figure 3-23).

Through a phase control, the waveform can be adjusted so that the value at the slit is at a minimum value as shown in Figure 3-23. If desired, it is also possible to adjust the phase control so that the waveform is at a maximum value at the slit as shown in Figure 3-24.

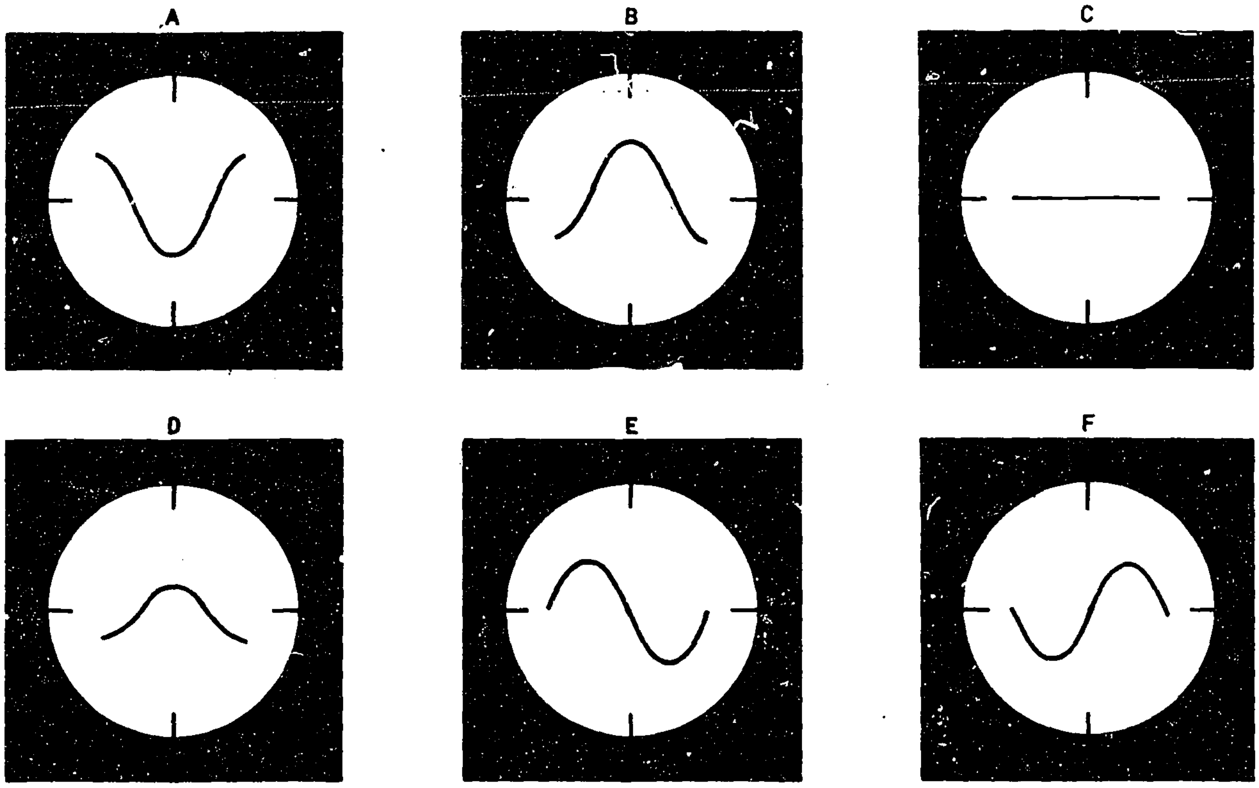


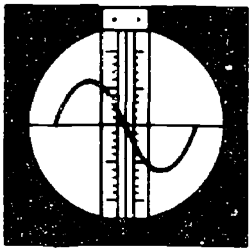
Figure 3-22. Typical Linear Time-Base Method Indication

(8) The significance of the waveform shown on the CRT depends upon how the initial conditions are established. For example, the waveform in Figure 3-25 represents a dimensional change of the test article dimension which is not the same as that of the reference standard. Under such conditions an output voltage would be developed and this would be seen on the CRT.

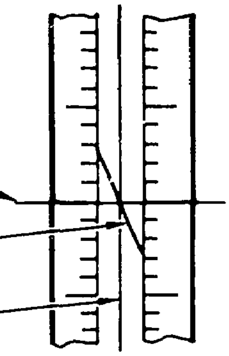
(9) The purpose of the phase control should be clearly understood by the NDT specialist. The period of the timing voltage is the same as the period of the cycle supplied by the generator; however, the phase of the timing voltage with respect to the generator voltage can be changed. Note in Figure 3-26 that the phase control (also called a phase shifter) is positioned between the generator and the timing voltage circuit. The purpose of this control is to shift the phase of the waveform on the CRT so that the waveform can be positioned properly with respect to the slit.

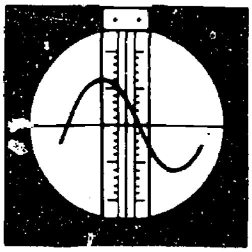
(10) Since the test coils and the properties of the articles produce phase changes, the waveform applied to the CRT's vertical plates is out of phase with the generator output waveform. The phase control, using

the same generator source, adjusts the timing voltage phase to some definite phase value. The waveform shown in Figure 3-26 represents the condition where the timing voltage is in phase with the waveform applied to the CRT's vertical plates.

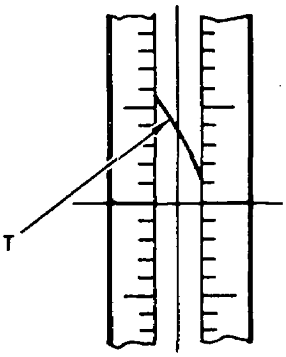


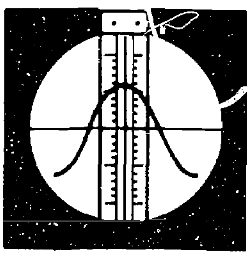
With the waveform adjusted so that it goes through zero, where the horizontal and vertical lines cross, we will see this in the slit . . .





If the waveform shifted 45 degrees to the right, the value at the slit will go up . . .





Then if the waveform shifted 45 degrees more to the right the value at the slit will go up still farther . . .

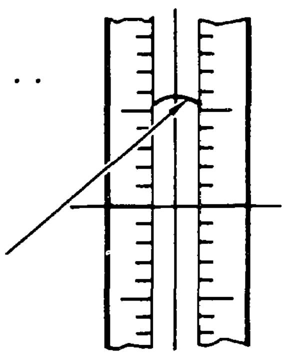
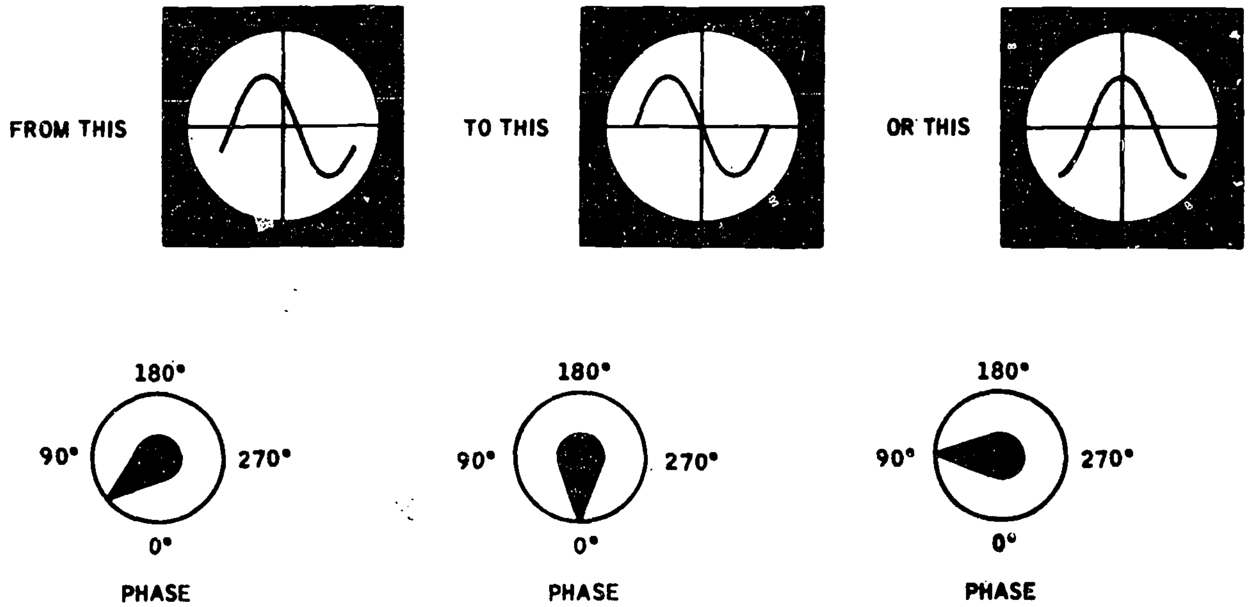


Figure 3-23. Vertical Transparent Slit

(11) Once the waveform shown in Figure 3-26 is obtained by setting the phase control, changes in this waveform will be caused by changes in the article's properties. These property changes produce phase shifts and cause the phase relationship between the input to the CRT's vertical plates and the timing voltage to change. This produces a change in waveform on the CRT. For example, the initial waveform



Note: By adjusting the PHASE control, the signal can be moved left or right to the desired position.

Figure 3-24. Phase Control

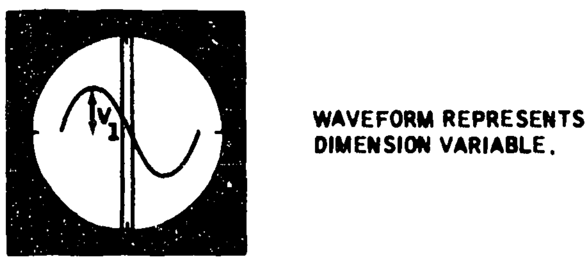


Figure 3-25. Dimension Variable

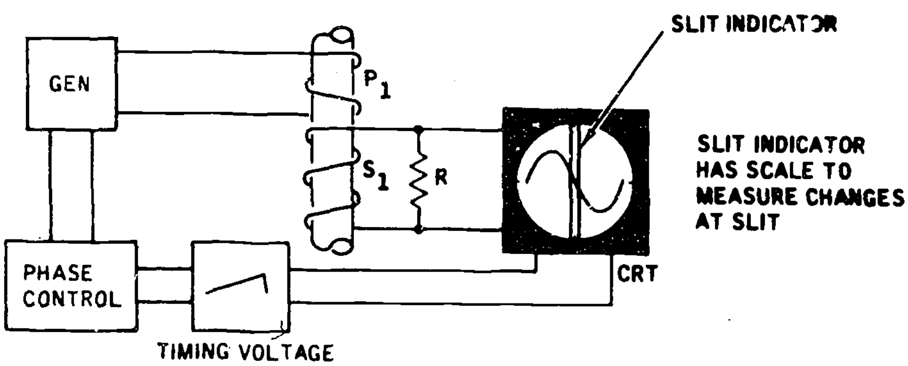


Figure 3-26. Phase Control

can be as shown in view A, Figure 3-27. A phase change can then cause this waveform to appear as shown in view B. Of course, it can also work the other way. View B can be the initial waveform as set by the phase control. A change in the article's properties can cause this waveform to change to that shown in view A. It's all a question of how you establish your initial waveform.

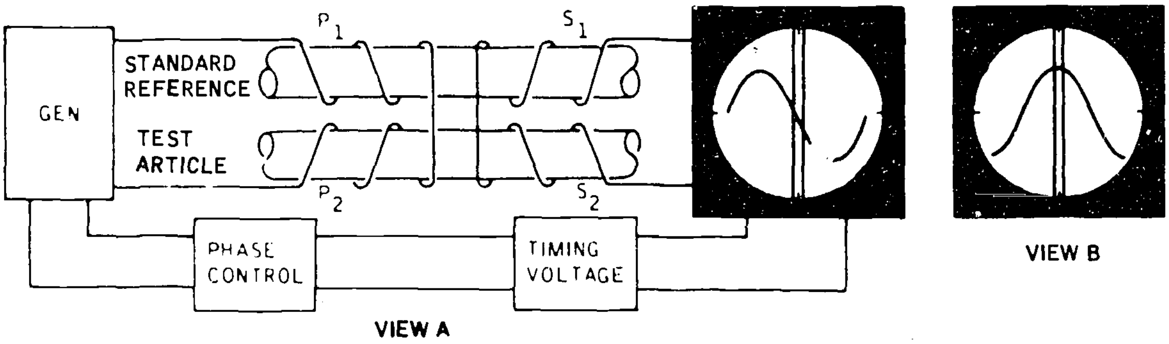


Figure 3-27. Phase Change

(12) If the test article used to obtain the display in Figure 3-26 is now replaced by an article with a conductivity difference rather than a dimension difference, the CRT waveform will change. For example, a test article is selected with a dimension property that is not the same for the reference standard. All other variables are the same for both the reference standard and test article. Under these conditions, an output voltage will appear across the secondary coils S_1 and S_2 and this will cause a waveform to appear on the CRT screen (Figure 3-27). This waveform can be any of a number of different displays, depending upon the setting of the phase control.

Using the phase control, the waveform is adjusted so that a zero value appears at the slit. This means that the maximum value of the waveform is 90 degrees out of phase with the slit. To cause this maximum value to appear at the slit will now require a voltage that is 90 degrees out of phase with the voltage being applied to the CRT's vertical plates.

The test article is now removed from the test coil. If a test article with identical properties to the reference standard is placed in the test coil, the CRT display will be a straight line. On the other hand if an article with a difference in conductivity is placed in the test coil, the waveform in view B, Figure 3-27 will be obtained. This represents a 90 degree phase shift and the slit value is now indicating a change in conductivity.

(13) The use of an article with both a difference in dimension as well as a difference in conductivity should also be understood by the NDT specialist. When both variables are present, the value at the slit will represent only the conductivity variable and the dimension variable will be suppressed. This is because the initial setup adjusted the phase so that the maximum value of the dimension variable was 90 degrees out of phase with the value at the slit. Using a dimension variable and adjusting the phase control to obtain the display shown in Figure 3-22 performed this task. Under this condition, the dimension variable is not reflected at the slit but at a position 90 degrees out of phase with the slit position.

(14) The linear time-base method has the capability of separating the two variables, since these two variables produce phase changes that are 90 degrees apart. Through the phase control, either variable can be selected for display at the slit.

4. ADVANTAGES AND LIMITATIONS

The primary advantage of phase analysis is the ability to separate the conductivity variable from the dimension and permeability variables. In doing so, the technique is limited to the frequencies and test conditions which cause the two sets of variables to produce phase changes that are 90 degrees apart. Phase analysis is also limited to the isolation of the conductivity variable as a total variable, since the technique does not provide a means of isolating the various factors which affect the conductivity variable. These factors represent another family of variables within the conductivity variable. Phase analysis is also limited by the NDT specialist ability to use the equipment and perform adequate interpretations of the CRT displays. It should also be noted that only one variable at a time can be suppressed by phase analysis.

304 MODULATION ANALYSIS TESTING SYSTEM

1. GENERAL

Of the three basic approaches to eddy current testing (impedance testing, phase analysis testing, and modulation analysis testing), the modulation analysis approach provides the separation of more variables.

2. DEFINITION OF MODULATION ANALYSIS TESTING

This technique is basically used for discontinuity analysis, since a discontinuity traveling through a test coil magnetic field modulates (changes) that field. If the coils are narrow and used differentially (i.e., very narrow field), then the discontinuity has a relatively large signal-to-noise ratio and its frequency of modulation is a function of the discontinuity's transit time through the coil's magnetic field.

As shown in Figure 3-28, a modulating device is placed between a fixed frequency generator and an indicating device. This modulation device will vary the effect applied to the indicating device.

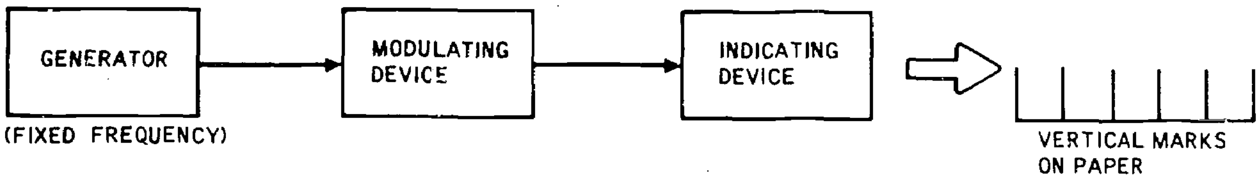


Figure 3-28. Modulation Analysis System

3. TECHNIQUE

The modulation analysis testing technique is shown diagrammatically in Figure 3-29 in terms of variables that can produce modulation. These are compared on the basis that the article is moving through the test coil magnetic field at a uniform speed. Each of these variables can produce an effect on the test coil.

a. Variables. Modulation analysis provides the means of removing unwanted variables from the output display. It thus becomes possible to separate the desired variable from the unwanted effects which are producing variations. An electronic filter will pass only certain frequencies through the filter. Thus, by using the proper filter, one can suppress all frequencies except those in a narrow band of frequencies. Using this technique, the display can then show only very low frequencies, low and very low frequencies, intermediate frequencies, or very high frequencies.

b. Differential Test Coil Arrangement. To enhance modulation analysis a differential test coil is used. Here two adjacent areas of the article are compared and a signal difference can be measured.

c. Dimension Changes. Usually in products to be tested, i.e., tubes, bars, etc., uniformity of dimensions is very good. To state it another way, when comparing dimensions in two closely adjacent areas of the article, the dimension changes slowly, therefore the modulation is a very low frequency.

d. Chemical Composition. Chemical composition, alloy changes, and heat treat changes are usually slowly changing along the length of the article. Therefore we have a low frequency modulation from these variables.

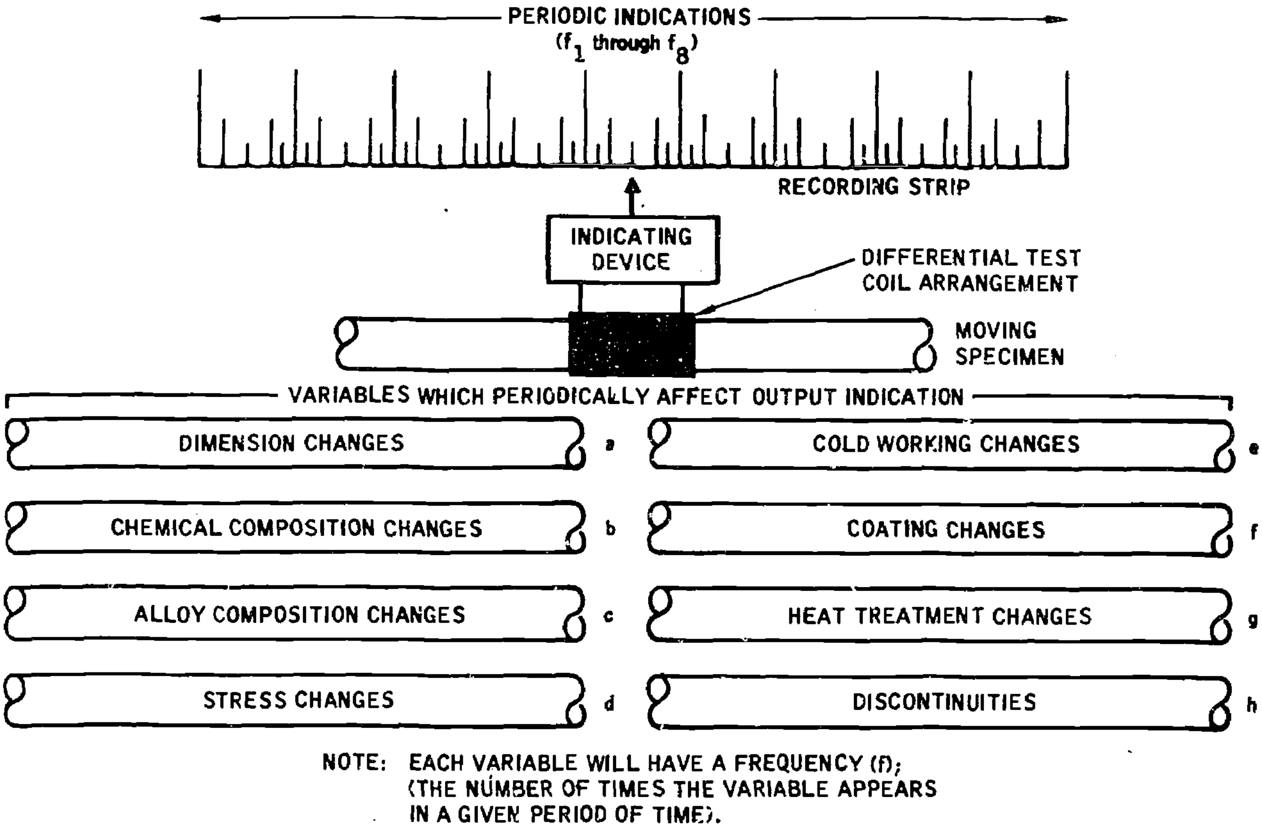


Figure 3-29. Modulation Analysis Testing

e. Lattice Effects. Changes in the atomic lattice due to cold working, stress changes, etc., can occur over small areas of the article. These smaller areas in the article do not affect the differential test coils equally, therefore, we have an intermediate frequency of modulation.

f. Discontinuities. Discontinuities of a small size tend to produce a relatively high modulation frequency.

g. Use. In a normal application which is primarily for discontinuities detection, the measuring instrument has adjustable frequency filters to allow selection of the information desired (like bass-treble control on hi-fi set). The discontinuity frequency is a function of discontinuity size, coil design, and the speed that the article moves through the test coil magnetic field.

4. ADVANTAGES AND LIMITATIONS

The modulation analysis approach provides a means of separating the variables to a greater extent than other testing methods. A major limitation is that the system is based on a moving article. Static test situations cannot be used.

305 EDDY CURRENT CALIBRATION REFERENCES

1. GENERAL

Like other forms of nondestructive testing, references material with known characteristics are used as standards. In some cases, the standard is an article with known chemical or alloy composition characteristics and no discontinuities. This reference standard is used as a basis for comparison. In other cases, artificial or natural discontinuities are intentionally added to an article to form a calibration reference.

2. NEED FOR ARTICLES AS STANDARDS

Articles as standards are used for several purposes. As shown in Figure 3-16 an article can be used as an external reference. For this arrangement the article has all the characteristics of an acceptable article. Articles with known variations from the acceptable article may be used in the initial setup of the system to suppress undesirable variables. Reference standards with known discontinuities are also used to verify the sensitivity of equipment as well as the overall performance of a testing system.

3. ARTIFICIAL AND NATURAL CALIBRATED REFERENCES

It is common practice to specify eddy current testing performance in terms of articles with discontinuities which can be described by written procedures and can therefore be duplicated. Both artificial and natural discontinuities can be used.

a. General Requirements. A reference is prepared by selecting an article which is identical in composition, history, and dimensions to the articles being tested. The article should be as free as possible of inherent discontinuities.

b. Artificial Discontinuities. Types of artificial discontinuities that can be used to simulate article discontinuities are longitudinal notches, circumferential notches, drilled holes, file cuts, pits, diameter steps, and indentations. Several methods exist for developing these discontinuities in an article.

c. Natural Discontinuities. Natural discontinuities can be developed or accumulated. For example, cracks can be developed by submitting a material to cyclic stress until a natural fatigue crack is generated. This can then be machined to produce a surface or hole crack of known depth. Natural discontinuities can also be accumulated over a period of time during routine testing of articles. These natural discontinuities can then be processed to provide reference values of known depths.

4. PERFORMANCE AND CALIBRATION REFERENCES

Articles can be classified as performance references or calibration references depending upon how the article is used.

a. Performance References. A performance reference is used to qualify a test system for a particular test. Such a reference is normally used at the beginning of the test to ensure that all controls are properly set and that the system performance is normal. The article is prepared with a range of discontinuities to ensure that the system can detect the variables of interest.

b. Calibration References. The purpose of a calibration reference is to ensure that the amplitude and phase characteristics of a test system does not drift during continuous testing. When the test equipment is used for extended periods of time the calibration of some components may change. Periodically the calibration reference is passed through the testing system to verify that the equipment is still calibrated and that amplitude and phase are stable. The types of discontinuities and their location in the calibration reference will not be the same as those in the performance reference because their function differs as test references.

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CHAPTER 4: EDDY CURRENT METHODS

400 GENERAL

Technological advances in the field of eddy current testing equipment has so broadened the scope of capabilities that today eddy currents are being used for the evaluation of: fatigue effects, depth of case, decarburization, film thickness, discontinuities, material hardness, alloy composition, material thickness, carbon content in steel melt, movement of surfaces in adverse environment, etc.

The article configuration, scope of the test, location of area of interest, type of environment, dictate the method, type of coil which would be required for the specific test.

Eddy current testing more so than any other form of nondestructive testing is strictly specialized. This makes the development of techniques which would be universal very difficult.

The three general groups which will be covered are conductivity testing, discontinuity testing, and coating measurement.

401 CONDUCTIVITY TESTING

1. GENERAL

One of the major applications of eddy current testing is the measurement of conductivity. This application is possible since most materials have a unique conductivity value determined by the materials chemical composition, its processing and method of manufacture. It should be noted that most pure metals, e.g., gold, copper, silver, etc., have definite conductivity values, whereas most alloys have broad values or ranges.

2. INTERNATIONAL ANNEALED COPPER STANDARD (IACS)

Standard conductivity has been defined by the International Electrochemical Commission in terms of the amount of resistance to be found in a specified grade of high purity copper when measured at 20C. (68F). This resistance amounts to approximately 0.15 ohms per gram meter, which has been arbitrarily designated as 100% conductivity.

Expressing conductivity in terms of International Annealed Copper Standard or % IACS is a convenient method of comparing one material with another. For example, a material with a conductivity of 50% IACS would be interpreted to mean that the conductivity when compared to the IACS would be only 50%.

3. EQUIPMENT SCALES

Equipment designed to measure conductivity indicates the conductivity in terms of the IACS percentage. Figure 4-1 illustrates a typical tester which has a scale expressing conductivity in terms of a percentage. Normally the range of the scale is a small segment of the total IACS range. For example, the range of the scale in the tester in Figure 4-1 may have a conductivity range of 60-110% IACS. Although some testers have a removable scale, the trend is toward specific conductivity ranges designed for a specific application as in Table 4-1.

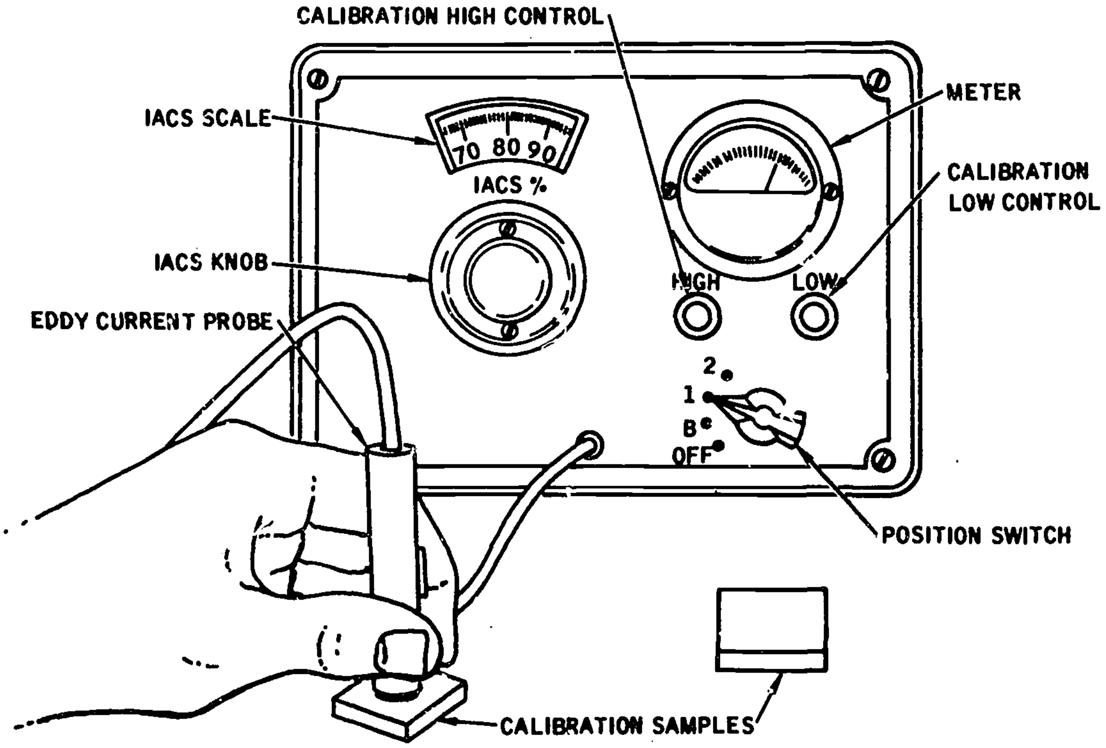


Figure 4-1. Typical Conductivity Tester

Table 4-1. Typical Scale Ranges

Scale Number	Conductivity Range %IACS	Resistivity Range In Micro-OHM-CM
1	1-5	43 UP
2	4-20	8.6-43
3	15-70	2.8-8.6
4	60-110	1.5-2.9

4. CALIBRATION

Calibration of eddy current conductivity testers is accomplished by the use of calibration samples (Figure 4-1). Normally two samples are provided, one for each end of the scale. A typical calibration procedure is detailed as follows:

a. Place position switch (Figure 4-1) to position B.

b. Check that meter indication falls in red area on right end of meter scale. This denotes that battery power is satisfactory.

c. Place position switch to position 1. (This is the low sensitivity position.)

d. Select calibration sample with the highest IACS value and, using the IACS knob, set this value on the IACS scale. (Scale has a centerline to permit setting of specific value.)

e. Press eddy current probe against selected calibration sample.

f. Adjust calibration HIGH control to obtain zero indication on meter scale.

g. Replace calibration sample with the IACS sample for the low end of the scale.

h. Press eddy current probe against the sample and adjust calibration LOW control to obtain zero indication on meter scale.

i. Perform final calibration by placing position switch to position 2 and repeat steps d through h.

NOTE: Because of interactions between the high and low sensitivity positions (1 and 2), it may be necessary to repeat the procedures several times to obtain zero indications on both positions.

5. CONDUCTIVITY MEASUREMENTS

The following paragraphs describe the measurement procedures, the interpretation, and the various factors related to evaluating the results.

a. Procedure. A typical measuring procedure is detailed as follows:

(1) Ensure that tester is calibrated.

(2) Ensure that article's temperature is approximately the same as the calibration samples.

NOTE: Normally the ambient temperature of the calibration samples and the article are the same, therefore, if calibration is accomplished immediately prior to performing conductivity measurements, the requirement of Step 2 is satisfied.

(3) Press eddy current probe against test article.

(4) Slowly rotate IACS knob until meter indicates zero.

(5) Observe value on IACS scale. This is the conductivity of the test article.

b. Interpretation. The typical tester shown in Figure 4-1 is a compact, portable, battery-powered instrument with a fixed frequency and with a probe matched to the tester. Accuracy is within ±3% of the scale reading which can be improved when the tester is calibrated within a range less than the full range of the scale.

(1) Since the tester has a fixed frequency and coil, the depth of eddy current penetration on a specific material will vary with the conductivity of the material. (Table 2-1). As the conductivity increases, the depth of penetration decreases. For example, for material "X" with a conductivity of approximately 12% IACS the depth of penetration is 0.080 inches; with a value of 98% IACS, the depth is 0.030. This means that conductivity measurements are being made only near the surface of the article, and are independent of the thickness of the article, providing that the article is thicker than the depth of penetration.

(2) Most eddy current conductivity testers are designed for use on nonmagnetic conductive materials. This, of course, is based on a magnetic material adding a second variable, permeability, and making it impossible to use established scales that relates readings to conductivity values. To measure magnetic materials, it would be necessary to saturate the material. Complete saturation may not be possible in some highly magnetic materials or in thick sections. However, where it is possible, saturation of the material would make the permeability value approximately one.

(3) In the measurement of a nonmagnetic conductive material, the IACS value is an absolute value and can be related to a material or group of materials as shown in Figures 4-2 and 4-3. It should be pointed out, however, that heat treat, cold working, aging and ambient temperatures all affect the conductivity value; therefore, the actual relationship of the measured value to the information in Figures 4-2 and 4-3 must be qualified. Normally, the conductivities of a number of acceptable articles are measured and correlated against actual physical testing so as to qualify the conductivity measurements as reference standards.

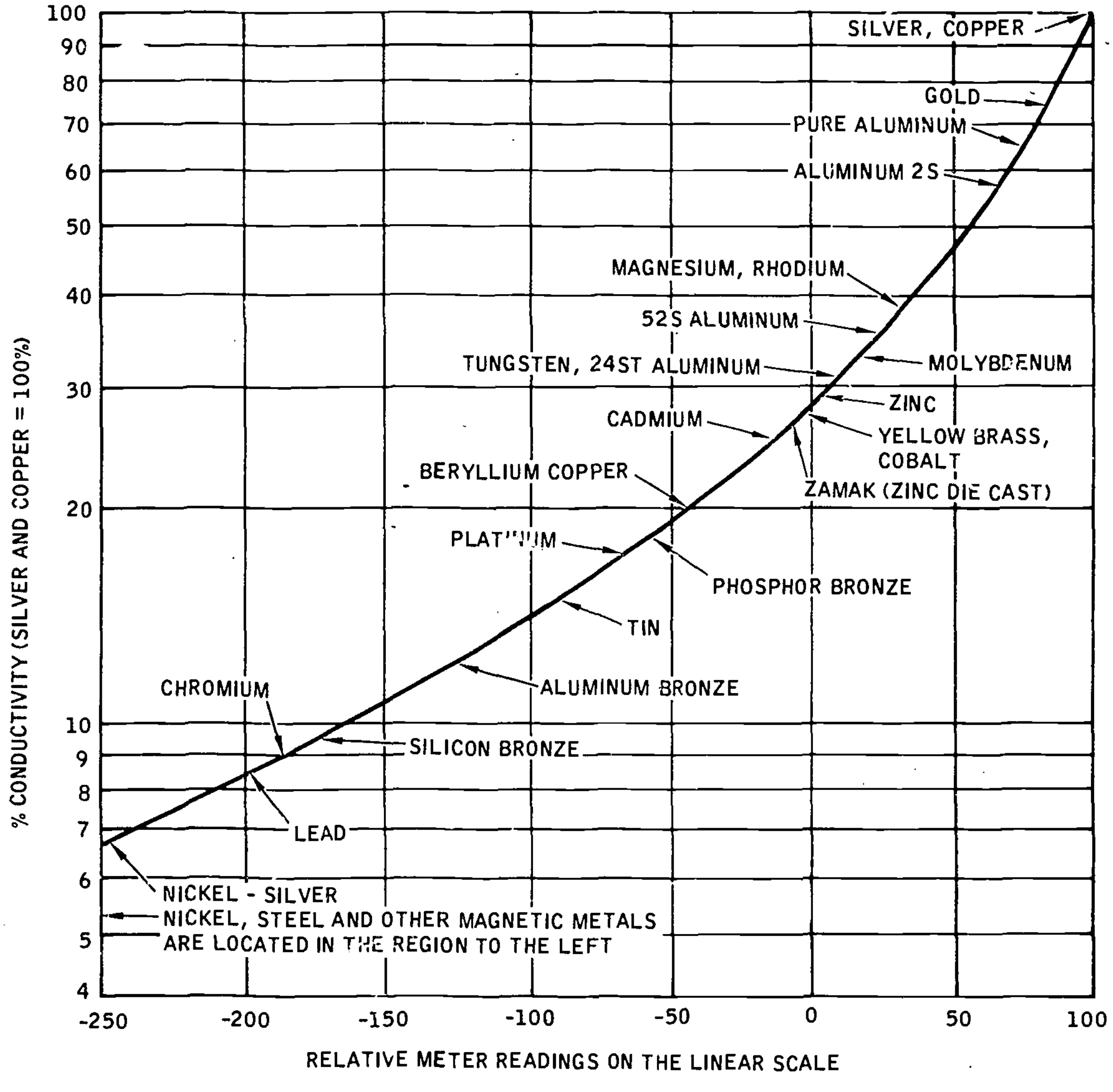


Figure 4-2. Relative Conductivity of Various Metals and Alloys Versus Eddy Current Meter Readiness

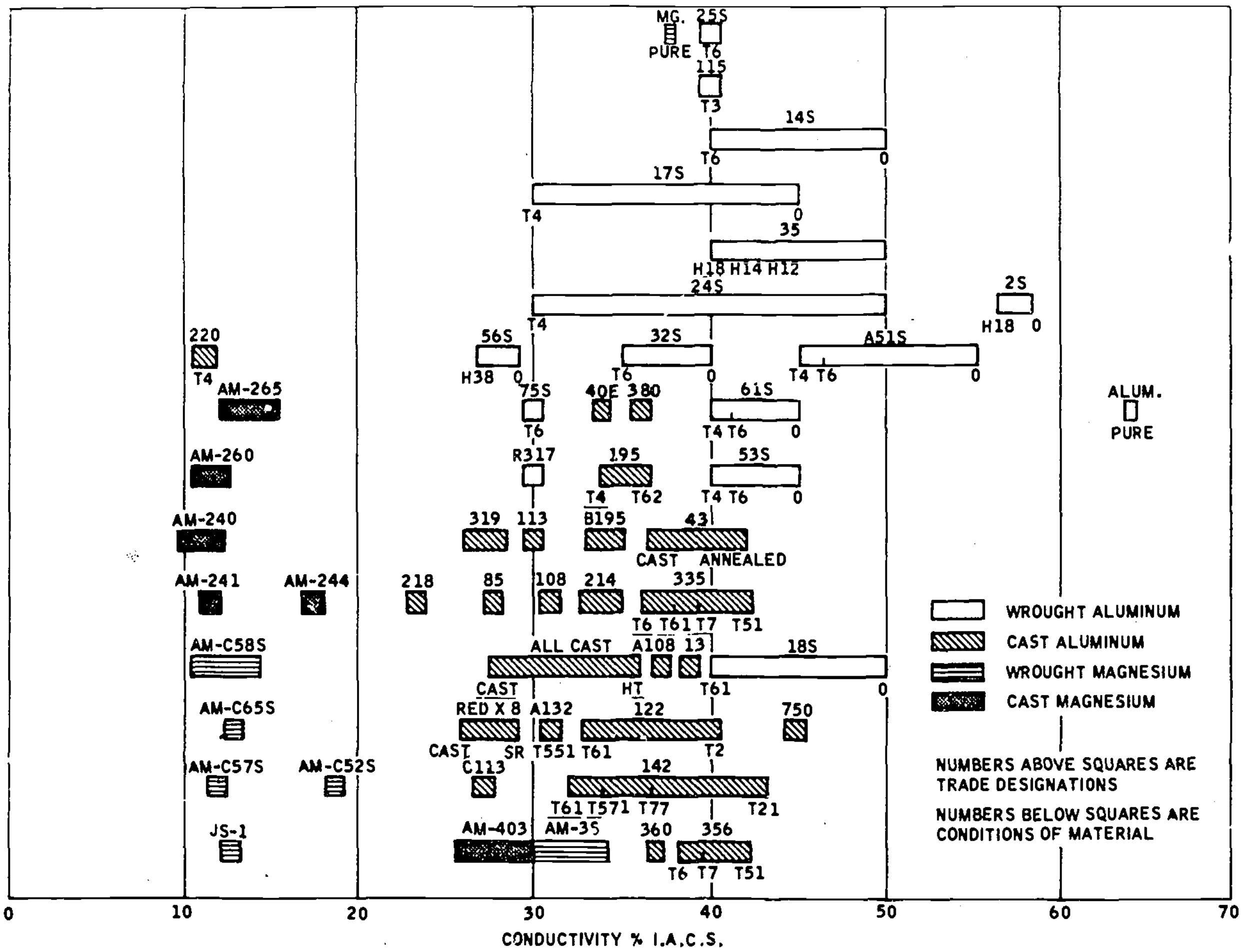


Figure 4-3. Electrical Conductivity of Aluminum and Magnesium Alloy

c. Sorting. Most nonmagnetic pure metals can be screened by the means of their conductivities. However in screening alloys the conductivity values frequently overlap. This overlapping is characteristic of the alloying elements which govern the conductivity.

Two general cases can be identified. In the first case, a number of materials have been mixed. Each material can be identified and its conductivity defined. With this information, it is then possible to sequentially measure each article in the mixed group and to separate the article based on the differences in conductivity. The sorting operation can only be performed when there is no overlap in the ranges of conductivity for each material. If the ranges overlap, it becomes impossible to determine which article falls in which material class. In the second case, a group of articles of the same material must be sorted based on the differences in conductivity between articles. For this condition, the absolute conductivity value for each article is not required. A typical procedure for performing sorting under this condition is detailed as follows:

(1) Ensure that tester is calibrated.

(2) Select article with maximum allowable conductivity.

(3) Select article with minimum allowable conductivity.

(4) Select article with conductivity that is halfway between maximum and minimum allowable values. Use this article to set value on IACS scale. Press probe against article.

(5) Rotate IACS knob to obtain zero indication on meter.

(6) Place probe against maximum allowable conductivity article, observe meter value, and record value.

(7) Place probe against minimum allowable conductivity article, observe meter value, and record value.

(8) Sort articles by pressing probe against test Reference Standard, observing meter indications, and accepting or rejecting articles based on the limits established by the maximum and minimum references and indicated on the meter.

d. Hardness Measurements. Eddy current conductivity testing can also be used to infer the hardness of a number of nonmagnetic materials. Usually conductivity decreases as hardness increases. A relative scale can be set up for this relationship by selecting two or more calibration samples which cover the range needed for the articles to be tested. These samples are measured by normal hardness techniques, e.g., Rockwell, then conductivity measurements are made and correlated. Table 4-2 illustrates how such information can be gathered regarding the hardness of a specific material. This information can be related to a range of conductivity values for the material. It thus becomes possible to use conductivity measurements rather than hardness measurements to infer the hardness of this specific material. It should be noted that other variables may not affect the article's conductivity but may affect its physical properties (Reference Note 1, Table 4-2). Caution must always be exercised in an implied hardness measurement by means of eddy current, for it is common that hardness measurements may be in gross error.

Table 4-2. Conductivity Values/R/C Hardness

ALUMINUM ALLOY - SHEET AND PLATE - BARE

MAT MAT'L	SPEC	COND.	STANDARD	SUPERFICIAL	BRINELL VALUE 10MM BALL 500 kg. LOAD	CONDUCTIVITY VALUE % OF IACS * ** (MATERIAL THICKNESS .050 & THICKER)
5456	MIL-A-19842	0	NO HARDNESS TEST DATA AVAILABLE			
		H321	NO HARDNESS TEST DATA AVAILABLE			
		H343	NO HARDNESS TEST DATA AVAILABLE			
6061	QQ-A-327	0	H75 MAX.			44.0 - 49.0
		T4	H91 MIN.	15T64 MIN.	57 MIN.	35.5 - 40.5
		T6, T651	E85 MIN.	30T47.5 MIN.	80 MIN.	40.0 - 45.0
7075	QQ-A-283	0	E77 MAX.	30T38.5 MAX.	70 MAX.	44.0 - 47.0
		T6, T651	B83 MIN.	30T72 MIN.	137 MIN.	30.5 - 34.5
	MMS-159	T73	B69 MIN.	(SEE NOTE 1 AT BOTTOM OF PAGE)		38.0 MIN.
7079	MIL-A-8877	T6, T651	NO HARDNESS TEST DATA AVAILABLE			30.5 - 34.0
7178		0				43.0 - 47 0
7178	MIL-A-9180	T6, T651	B86 MIN.	30T74 MIN.	145 MIN.	30.0 - 34.0
7079		0				44.0 - 47.0
7079		T6, T652				30.5 - 34.0

NOTE 1: THIS VALUE IS TO BE USED ONLY TO DETERMINE THAT MATERIAL IS NOT IN THE "O" CONDITION. IT DOES NOT IN ANY WAY INDICATE WHETHER OR NOT THE MATERIAL HAS BEEN PROPERLY HEAT TREATED TO THE T73 CONDITION.

* NORMAL ROCKWELL TESTING WILL BE USED ON MATERIAL THICKNESSES OUTSIDE THE RANGES AUTHORIZED FOR CONDUCTIVITY TESTING.

** A ROCKWELL SAMPLE SHALL BE TAKEN FOR THOSE LOTS TESTED ENTIRELY BY CONDUCTIVITY TESTING.

e. Heat Treatment Variations. In the processing of materials and articles, heat treatment and quenching techniques are used which produce metallurgical variations in the articles. These variations produce changes in conductivity (nonmagnetic material) which can be detected by eddy current testing. Such conductivity tests are being used as in-process controls. Conductivity tests can also be used to evaluate damage caused to structures as a result of excessive heat. For example, if the conductivity of a (structure) material is established and then the structure is exposed to excessive heat, it is possible to determine the degree of physical change due to the exposure. In many cases, localized heating of a structure may occur; therefore, a comparison can be made between the two areas on the same structure. The strength of an article will decrease and the conductivity increase in direct relation to the amount of heat treatment received by the article; therefore, through conductivity measurements, it becomes possible to monitor changes in an article's strength as shown in Table 4-3.

Table 4-3. Physical Properties of Copper - 1% Chromium Alloy

CONDITION	YIELD POINT KSI	UTS KSI	ELONGATION, % ON 2 IN.	HARDNESS, DPH	CONDUCTIVITY, * IACS
AS CAST	9	27	42	60	59
HOT WORKED	18	33	40	71	69
AS HOT WORKED AND QUENCHED FROM 1050°C	10.2	29	40	64	38
AS QUENCHED AND AGED AT 500°C FOR 1 HR	39.2	54.4	25	152	85

f. Depth of Penetration. In performing conductivity testing, it is necessary to keep in mind that eddy current testing is essentially a surface testing technique. In the case of a plane conductor, the current falls off exponentially with depth below the surface. (Figure 4-4.) The standard depth of penetration in a plane conductor in a uniform field is the depth at which the current is equal to 1/e (37 percent) times its value at the surface. The greater the frequency, permeability or conductivity, the less the depth of penetration. For nonmagnetic materials whose value of permeability (μ) is approximately one, the desired penetration can be controlled by the frequency selection.

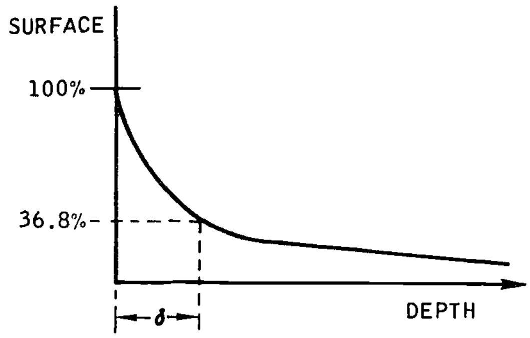


Figure 4-4. Eddy Current Strength Drops Off With Distance From Surface

g. Temperature. A change in the temperature of an article will change the electrical conductivity due to the increase in lattice paramete s and thermal vibration of the atom. In several techniques this increase in lattice size and the resulting change in conductivity can be used to measure the temperature of an article in an adverse environment. However in most applications where conductivity is being measured, the control of the reference standard and the article's temperature may be of utmost importance. All tests which are critical in nature should have the testing temperature range specified.

402 DISCONTINUITY TESTING

1. GENERAL

A second major application of eddy currents is the detection of discontinuities. In such detection eddy currents flow in regular patterns within an article and a discontinuity changes this pattern. (Figure 4-5.) As the pattern changes, the output indication changes.

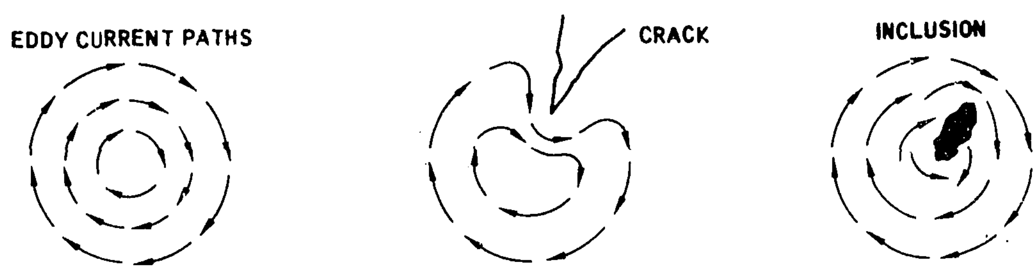


Figure 4-5. Eddy Current Pattern Changes

Detection of discontinuities depends directly on the design of the specific types of eddy current detectors. It also depends directly on whether manual or automatic methods are used. The following paragraphs will describe the application of the impedance method of detection, using a typical meter indication. Subsequent paragraphs will cover other ways of performing discontinuity testing. Figure 4-6 illustrates a typical eddy current discontinuity detector. This is the same detector described in Chapter 3. In using this detector, it should be recalled that the detector does not provide absolute measurements. A change in the meter indication simply means that the article has changed the impedance of the test coil. If the article's characteristics are constant, the meter indication is constant. On the other hand, a change in characteristics will change the coil's impedance which, in turn, will cause a change in the meter indication.

2. CALIBRATION

The typical impedance (discontinuity) detector (Figure 4-6) does not require calibration immediately prior to use. It is sufficient to turn on the detector and allow 15 minutes of warmup prior to use. Turn on the detector as follows:

a. Connect probe to PROBE receptacle.

b. Connect detector to power source.

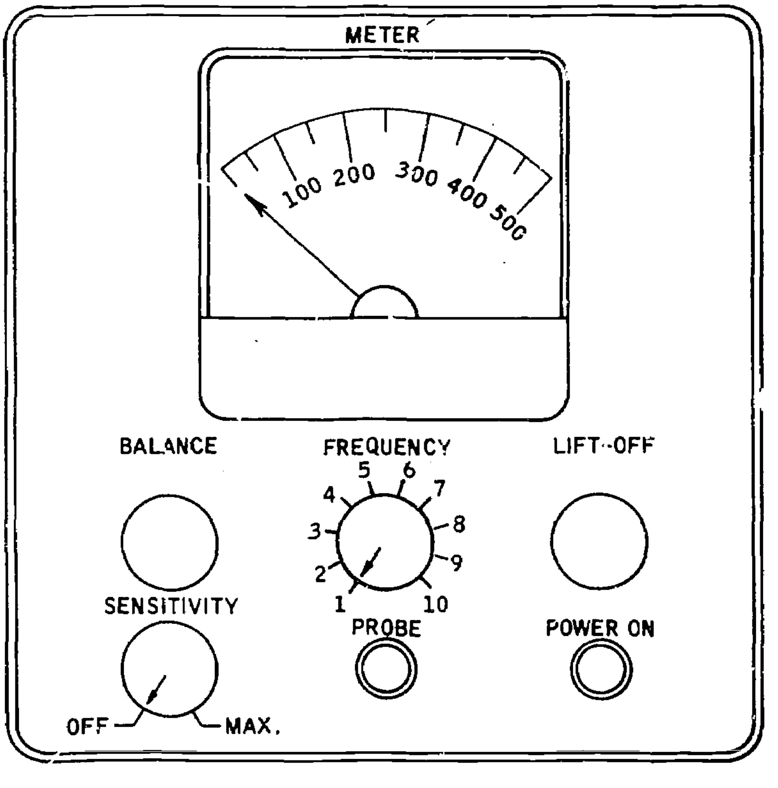


Figure 4-6. Typical Impedance (Discontinuity) Detector

c. Rotate SENSITIVITY control clockwise to MAX position. This turns on the detector and sets the sensitivity of the detector to the maximum position.

d. Check that POWER ON light comes on.

3. DISCONTINUITY DETECTION

Use of a typical impedance (discontinuity) detector is a two step process: (1) preparation and (2) detection. In using the detector, it is important to know that the depth of penetration can be changed by the FREQUENCY control. Ten positions are shown in Figure 4-6. The lowest position (position 1) is the highest frequency (e.g., 134 kilocycles); the highest position (position 10) is the lowest frequency (e.g., 54 kilocycles). Rotating the control from the lowest position to the highest position represents an increase in depth of penetration. Depth of penetration increases as the frequency is decreased. The LIFT-OFF control is a fine frequency (vernier) control for any frequency selected by the FREQUENCY control. In normal practice, the FREQUENCY control is set to a position and, through the LIFT-OFF control, the final frequency is selected. The FREQUENCY control is thus a coarse frequency control while the LIFT-OFF control is a fine frequency control.

a. Preparation. Preparation for discontinuity detection is accomplished as follows.

(1) Ensure that detector is turned on and SENSITIVITY control is rotated clockwise to MAX position.

(2) Turn BALANCE control counterclockwise to maximum position.

(3) Turn LIFT-OFF control counterclockwise to maximum position.

(4) Set FREQUENCY control to position 1. (Or to specified setting, if known.)

(5) Press probe on surface of reference. Use reference that has been previously determined to be acceptable.

NOTE: Eddy current detection is a relative testing technique. Article references must be established for comparison.

(6) Adjust BALANCE control to obtain mid-range indication (approximately 250 microamperes on meter scale).

(7) Lift, then return probe to reference's surface, noting the direction of meter deflection.

(8) If meter deflects downscale (towards lower value), rotate FREQUENCY control to position 2 (or next highest number) and repeat steps (6) and (7). If necessary, repeat procedure, using position 3 (or next highest number) until deflection in the upscale direction is obtained.

(9) Place sheet of ordinary writing paper (0.002 to 0.004 thickness) between probe and article.

(10) Slide paper out from under probe and note direction of meter deflection.

(11) Rotate LIFT-OFF control in clockwise direction and note direction of meter deflection.

(12) Verify that meter deflection direction in step (11) is the same as in step (10). If it is not the same, rotate FREQUENCY control to the next highest position number and adjust BALANCE control to obtain mid-range indication.

(13) Repeat steps (9) through (12) until no meter deflection occurs when paper is removed from under probe.

(14) If desired, the sensitivity can now be reduced by rotating the SENSITIVITY control in the counterclockwise direction. This reduces the spread as displayed on the meter.

b. Detection. Eddy current discontinuity detection, using the impedance method, is a gross detection system based on the detection of changes from a standard reference. The article, through the regular eddy current patterns within the article, is the reference. As the eddy current test coil probe is moved across the article's surface, a meter deflection will indicate a change from a standard reference. The reason for the change cannot be determined by observing the meter deflection. The NDT specialist only knows that something within the article has changed.

c. Interpretation. Since a number of factors within the article affect the test coil, the significance of the deflection change depends upon the specific test application, the NDT specialist's experience, and the availability of standard references with artificial or natural discontinuities. It is also necessary to keep in mind that the depth of penetration varies with the test frequency: therefore, the depth of testing is not constant. One must also realize that eddy current testing is basically a surface testing technique which is limited by the depth of penetration. When the depth of the article is greater than the depth of penetration (the normal case) 100 percent testing of the article is not being accomplished throughout all areas of the article.

403 COATING/PLATING THICKNESS TESTING

1. GENERAL

Measuring the thickness of a coating or plating on the surface of an article is another major eddy current application. Two approaches are possible, depending upon whether the coating is conductive or nonconductive.

2. CONDUCTIVE COATINGS

If the coating (or plating) is conductive, the conductivity of both the coating and the article can be measured by the use of an impedance (conductivity) tester (Figure 4-1). The impedance (discontinuity) detector (Figure 4-6) may also be used to detect changes in thickness. Since the impedance (discontinuity) detector normally has a means of changing the test frequency, the detector is superior to the discontinuity tester for certain applications. Through the use of the frequency selector the depth of eddy current penetration can be adjusted so that the depth is just slightly greater than the thickness of the coating. Under this condition, maximum sensitivity in the coating area is obtained. In normal practice, no calculations are required since calibration curves (Figure 4-7) are prepared which relate thickness to meter indications. Such curves are prepared for each type of measuring instrument, probe, and coating. A group of articles with varying thickness are prepared and used to establish the initial calibration curve. By the use of the curves, it is only necessary to observe the meter indication, locate the observed value on the curve, and note the thickness related to this value on the curve. The validity of the test requires that the test frequency be specified and the instrument is periodically calibrated. It should also be realized that discontinuities may affect the meter indication.

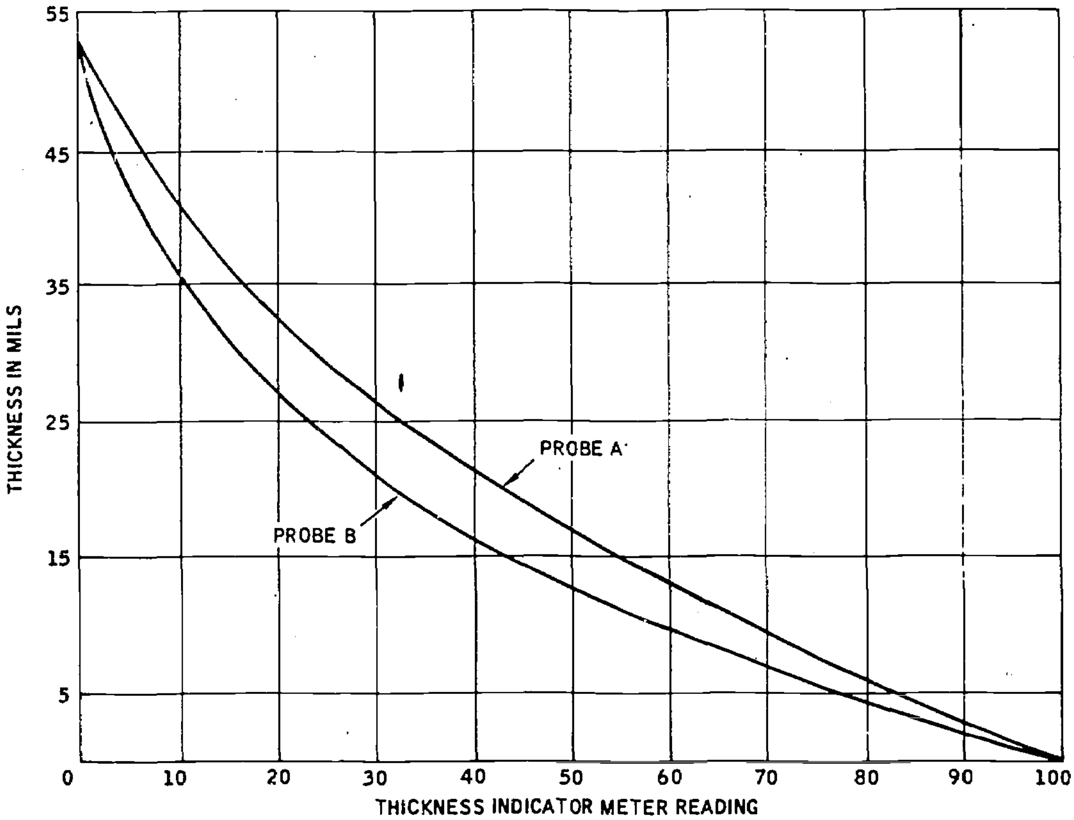


Figure 4-7. Typical Calibration Curve for Thickness Testing

3. NONCONDUCTIVE COATINGS

Because nonconductive coatings do not have eddy currents, such coatings can not be measured by the direct use of conductivity measurements. For such coatings, the lift-off effect property of surface coils is used. Variations in the thickness of a nonconductive coating cause a change in the distance between the test coil (probe) and the conductive area of the article. A change in distance produces a change in the output indication. The impedance (discontinuity) detector (Figure 4-6) may be used to sense such a change. Normally, standard references with specific thickness are prepared to provide a basis for comparison. The lift-off effect is a sensitive effect; therefore, it is important to maintain constant pressure on the probe to ensure that the probe pressure does not produce lift-off effects. Spring-loaded probes are particulary useful in performing thickness measurements on nonconductive coatings.

4. COATING CONDUCTIVITY VS BASE MATERIAL CONDUCTIVITY

Although coatings may be classified as conductive or nonconductive, the technique and accuracy of measurement is dependent upon the relative degree of conductivity between the coating and its base material.

As a general rule, coatings may be divided into the following categories:

a. Metal coatings having a higher conductivity than the base metal, i.e., copper, zinc, cadmium on steel.

b. Metal coatings having a lower conductivity than the base metal, i.e., chromium or lead on copper.

c. Nonconductive coatings on a metallic base, i.e., anodize or paint on aluminum alloy, organic coatings on metals, etc.

d. Metal coatings on a nonconductive base material, i.e., metallic film on glass, ceramic or plastic, etc.

5. USE OF SPECIAL THICKNESS TESTING EQUIPMENT

Special eddy current equipment is available for determining coating thicknesses. This equipment is normally limited to special applications (a specific thickness) from micro inches to several thousands of an inch.

404 NONCONDUCTIVE ARTICLES

Through the lift-off effect it is also possible to measure the thickness of nonconductive articles. This is accomplished by placing the nonconductive article on a conductive surface and inducing eddy currents into the conductive surface. Special commercially available units are used for this purpose and some units can measure up to 3 inches of nonconductive material.

405 TESTING FERROMAGNETIC MATERIALS

When eddy current testing techniques are applied to magnetic materials, trouble is experienced in resolving the measurement. The presence of permeability greater than one interferes directly with the indications because of the masking and opposing signal. It can be compared to a perfect conductor where the depth of penetration is almost zero. This permeability can be reduced to nearly one (air equivalent) by means of saturation. Saturation can be accomplished by a direct current magnetic field, or if the test area is small, it is possible to use a saturating magnetic field from a permanent magnet. Once the permeability factor is eliminated, eddy current tests can proceed as if testing nonmagnetic materials (approximately the same depth of penetration).

When elimination of the permeability variable is not necessary, it is possible to interpret test indications by means of a cathode ray presentation.

406 PHASE ANALYSIS

1. GENERAL

As described in Chapter 2, the technique of phase analysis can be applied to eddy current testing. The analysis can be performed by the NDT specialist on a manual basis or it can be performed by phase analysis circuits which are a part of the testing equipment. For NDT specialist interpretation, three phase analysis methods have been identified: vector-point method, ellipse method, and linear time-base method. These methods are described in Chapter 2.

2. APPLICATION OF VECTOR-POINT METHOD

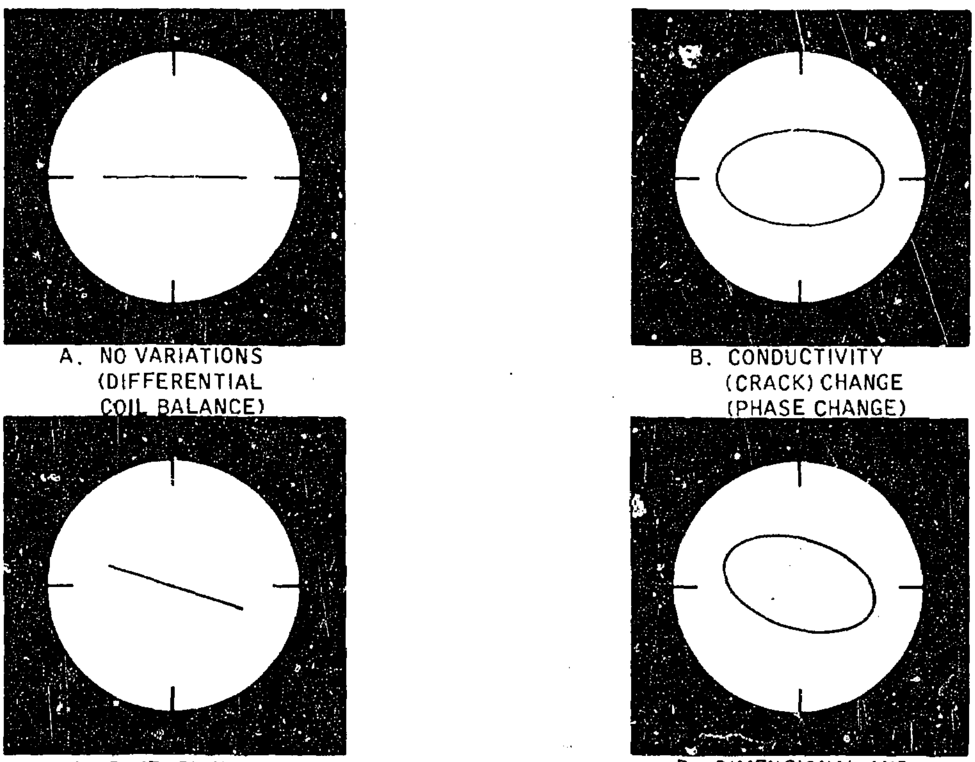
Figure 3-18 illustrates a typical vector-point method. In this method, the cathode ray tube indication is a dot of light and two sets of test coils are used; one for the standard article and one for the test article. Testing can be accomplished on either a manual or automatic basis. Through controls it is possible to separate the conductivity variable from the permeability and dimensional variables and to establish limits. Setup for the vector-point method is accomplished by using a test article with a specific variation. The article is placed in the test coil and is compared with the standard reference. Through equipment controls, the cathode ray tube dot is positioned so that movement of the dot only reflects the desired variation. That is, if by the equipment controls it was established that conductivity variations in the test article move the point of light up and down, any other variables will move the point horizontally. With the controls, the horizontal movements can be held to a minimum and the observer or recorder will see only the vertical movement. Thus, only conductivity changes will be detected. The maximum movement of the dot is established by the test article, and through scales on the CRT or through circuits within the CRT equipment, any dot values greater than the maximum limits are the basis for discrepancy evaluation of the test article. The dot indication can be related to sorting gates which automatically separate the articles based on the limits initially established by the article and indicated by the dot.

3. APPLICATION OF ELLIPSE METHOD

The ellipse method is described in Chapter 3 and illustrated in Figure 3-19. Figure 4-8 shows typical CRT indications. Like the vector-point method, the ellipse method uses two sets of test coils with the test article being balanced by a reference standard. When both reference standard and test article have the same properties, a condition of balance exists. This is shown in View A of Figure 4-8.

a. Setup. Initial setup for test is accomplished by using a test article with a known variable. This article is placed in the test coil and is compared with the reference standard. Through controls in the CRT equipment, the indication is adjusted so that a change in indication from View A Figure 4-8 to View C represents a dimensional change. This is the dimensional change in the test article used to establish the initial setup.

b. Test. Test is accomplished by manually or automatically passing test articles through the test article coil and observing the CRT indication.



A. NO VARIATIONS (DIFFERENTIAL COIL BALANCE)

B. CONDUCTIVITY (CRACK) CHANGE (PHASE CHANGE)

C. DIMENSIONAL (VOLUME CHANGE)

D. DIMENSIONAL AND CONDUCTIVITY (CRACK) CHANGES

Figure 4-8. Typical Ellipse Method Cathode Ray Tube Indications

c. Interpretation. The ellipse method provides indications of two variables at the same time. A change in dimension is indicated by the orientation of the ellipse. If the test article has only a dimensional variation, the ellipse will be a straight line which will be at some position (e.g., View C in Figure 4-8) other than the horizontal position shown in View A. If the article contains only a conductivity change, then the horizontal straight line will change to an ellipse (View B). On the other hand, when both a change in dimension as well as a change in conductivity exists, then a display such as shown in View D will be obtained. The orientation of the ellipse depends upon how the initial conditions are established and the phase relationships. Typical ellipse orientations are shown in Figure 4-9. The initial setup may establish the straight line indication at some angle other than the horizontal position shown in View A of Figure 4-8. Since this angle can be related to the scales on the front of the CRT, it is only necessary to establish a reference position. Detail interpretation of ellipse patterns depends upon the specific application; therefore, detail interpretation information will not be provided in this handbook.

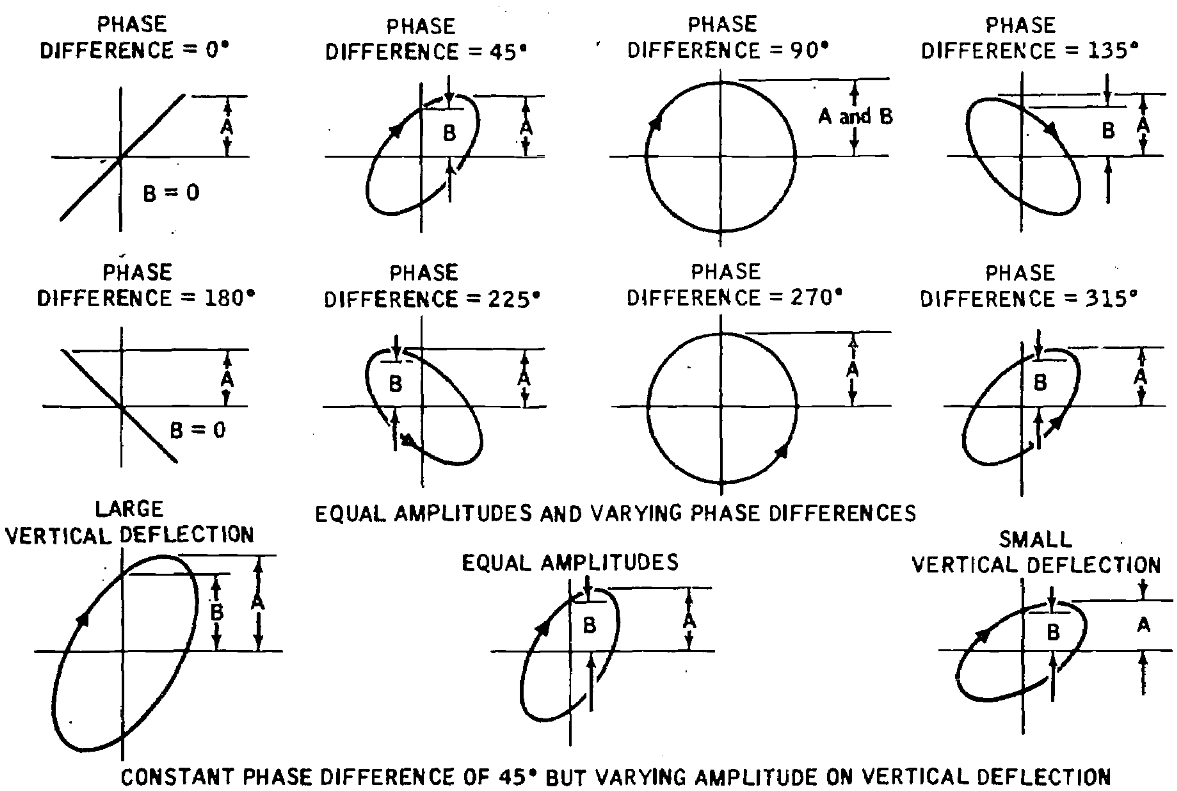


Figure 4-9. Typical Ellipse Orientations

4. APPLICATION OF LINEAR TIME-BASE METHOD

The linear time-base method is described in Chapter 3. Figure 4-10 shows typical CRT indications. In the linear time-base method two sets of test coils are used. A reference standard is used to balance the properties of the test article. In normal application, the reference standard may not completely balance the test article; therefore, balance controls on the CRT equipment are used to accomplish the final balance between the coil containing the reference standard and the coil containing the test article.

a. Setup. Because of equipment differences it is not possible to provide detail setup procedures in this handbook; therefore, only the general approach to setup will be described. Setup is accomplished as follows:

(1) Select two identical standard articles.

(2) Place one standard article in the reference standard test coil. (Either test coil may be used as the reference standard test coil; however, once this test coil has been established as the standard it should be retained as the standard.)

(3) By observing the CRT display and operating the CRT controls, obtain the indication shown in Figure 4-11.

(4) While observing the CRT display, slowly move reference standard back and forth in test coil. The center of the CRT display (View A) will move up or down. Position reference standard so that center of curve moves towards lower edge of CRT. As the reference standard passes through the center of the coil's magnetic field, the curve will reverse its downward movement and will begin moving upward. Since all testing should be done with the reference standard in the center of the coil's field, reposition the reference standard so that the CRT is as close as possible to the point where the curve reverses and moves upward. If necessary, secure the reference standard in this position by using tape, clay, or wax.

(5) At this point, a transparent sheet may be fitted to the CRT screen and the test level for the particular test may be set by controls on the CRT equipment. Normally, this will cause the bottom of the curve to drop out of sight. This is normal.

(6) Place a second reference standard in the second test coil. Position the article so that it is in the same relative position as the article in the reference standard test coil.

(7) Observe CRT display. When article is properly positioned, the CRT display should be a straight line as shown in Figure 4-12. For volume testing, guides would be used to ensure proper

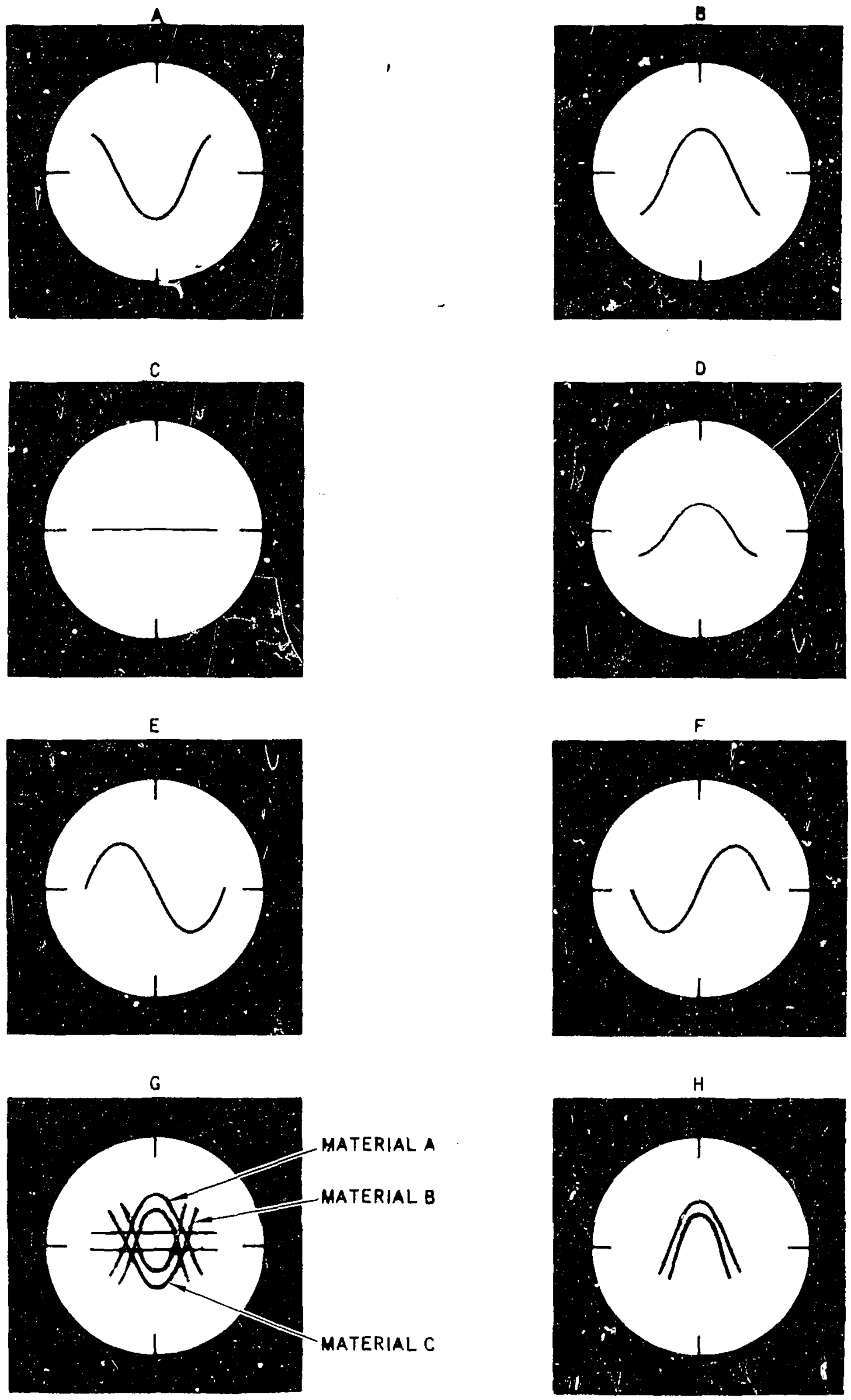


Figure 4-10. Typical Linear Time-Base CRT Indications

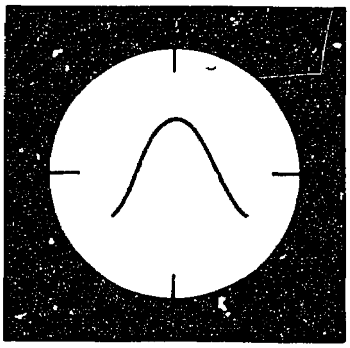


Figure 4-11. Balanced Condition

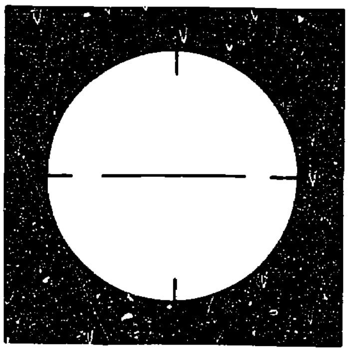


Figure 4-12. Combined Properties of Two Articles

positioning of the test articles placed in the second test coil. The straight line is the result of combining the properties of the two articles.

(8) If the CRT display is not a straight line, the CRT balancing coils may be used to balance the coils to develop the straight line. A slight ripple is also acceptable.

(9) At this point it is possible to perform various types of testing. Further setup procedures depend upon the type of test; therefore, final setup procedures must be included in the specific test.

b. Material Sorting Test. This test is the process of sorting various types of materials based on the displays and display limits shown on the CRT. This sorting is based on each material having distinct properties. Figure 4-13 illustrates the results of passing three separate materials through the same test coil. If a group of articles made from material A are passed through a test coil, each article will develop a characteristic display. This can be drawn on the transparent sheet covering the front of the CRT screen. The result will be a band of variation as shown in Figure 4-13. The same procedure can be followed for articles from

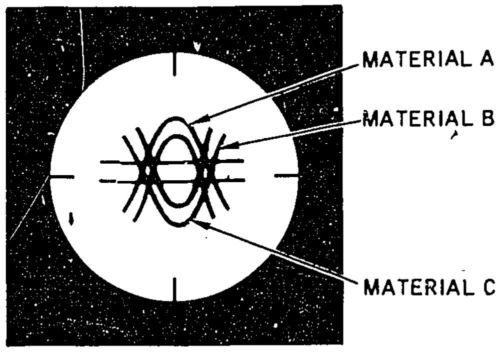


Figure 4-13. Display of Three Different Materials

materials B and C. If the bands do not overlap, it is possible to sort the three materials based on the limits set for each band.

c. Article Sorting Test. A group of articles can be sorted following the same procedure used for material sorting. When an article sorting test is accomplished, the CRT display may be changed to fit the specific test. This depends upon whether it is desirable to have the value at the slit a zero value or a maximum value. Typical applications are detailed as follows:

(1) For a maximum slit value, two standard articles may be used to establish the initial display shown in Figure 4-12.

(a) If test articles are then passed through the test coil a display such as shown in View A Figure 4-14 may be obtained. Limits can be established at the slit, and articles accepted or rejected based on the limits. View B, Figure 4-14, indicates the band of variation which can be drawn on the transparent sheet covering the CRT.

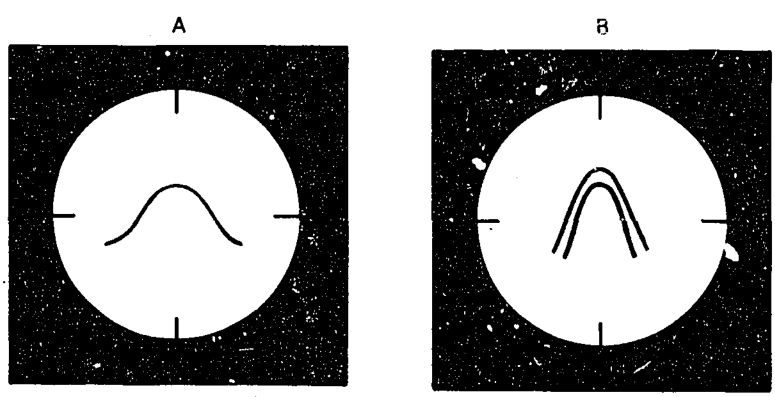


Figure 4-14. Band Variation

(b) In some applications it may be desirable to use a definite display as a basis for comparison. This is possible by using the CRT control to offset the initial balance between the test coils. When this is done, a display such as shown in View A of Figure 4-14 can be obtained. This display is drawn on the transparent screen (Figure 4-15) in front of the CRT and is used as a basis for comparison. When a test article is placed in the test coil, the display should match the display drawn on the transparent screen. The NDT specialist evaluates the CRT display against the display drawn on the transparent screen and accepts or rejects the article based on how well the two displays match.

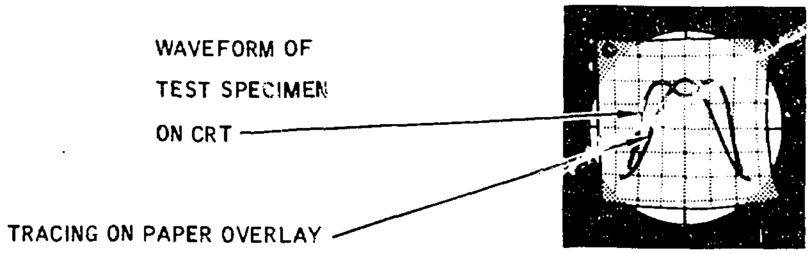


Figure 4-15. Transparent Screen Display

(2) For a minimum slit value, two standard articles may be used to establish the initial display shown in Figure 4-12. In establishing a minimum value at the slit, it is necessary to realize that a dimensional change or a permeability change will produce a phase change that is 90 degrees out of phase with the phase change produced by a conductivity change. The value at the slit can be made to represent either a conductivity change or a dimensional change (normally direct current saturation is used to make the permeability variable a constant). The following procedure will establish the conductivity variable as the value at the slit. By reversing the values, the same procedure can be used to establish the dimensional variable as the value shown at the slit. The conductivity variable is established at the slit as follows:

(a) Select a test article with a dimension that is not the same as the reference standard and position this article in the test coil.

(b) Using the phase control on the CRT equipment, adjust the display to obtain the display shown in Figure 4-16. The value at the slit should be zero.

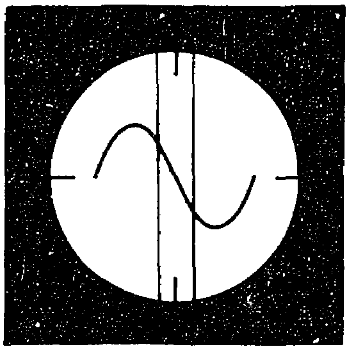


Figure 4-16. Conductivity Display

(c) Replace test article with article containing maximum allowable value of conductivity. Observe and record the value at the slit. Repeat procedure, using the article containing minimum allowable value of conductivity.

(d) With the slit values established, pass test articles through the test coil and accept or reject based on established limits. Articles are being tested for the conductivity variable only.

d. Interpretation. The linear time-base method provides a number of specific indications. The actual display and the interpretation depends upon the specific test. For many situations, the value at the slit can be read directly so interpretation is simplified. It is only necessary to ensure that the slit value limits are not exceeded. For the condition where a definite display is used with a maximum value at the slit this display is drawn on a transparent sheet to establish a standard, interpretation is a matter of experience. The NDT specialist must know to what extent the CRT display from a test article must match the display on the transparent sheet.

407 MODULATION ANALYSIS

1. GENERAL

The modulation analysis technique is described in Chapter 2. Typical indications are shown in Figure 4-17. Figure 4-18 illustrates a typical modulation analysis unit with three recorder displays for the same test condition. As shown in Figure 4-18, through the use of the FOURIER CONTROL switch, the discontinuity can be separated from the other variables which are affecting the test coil.

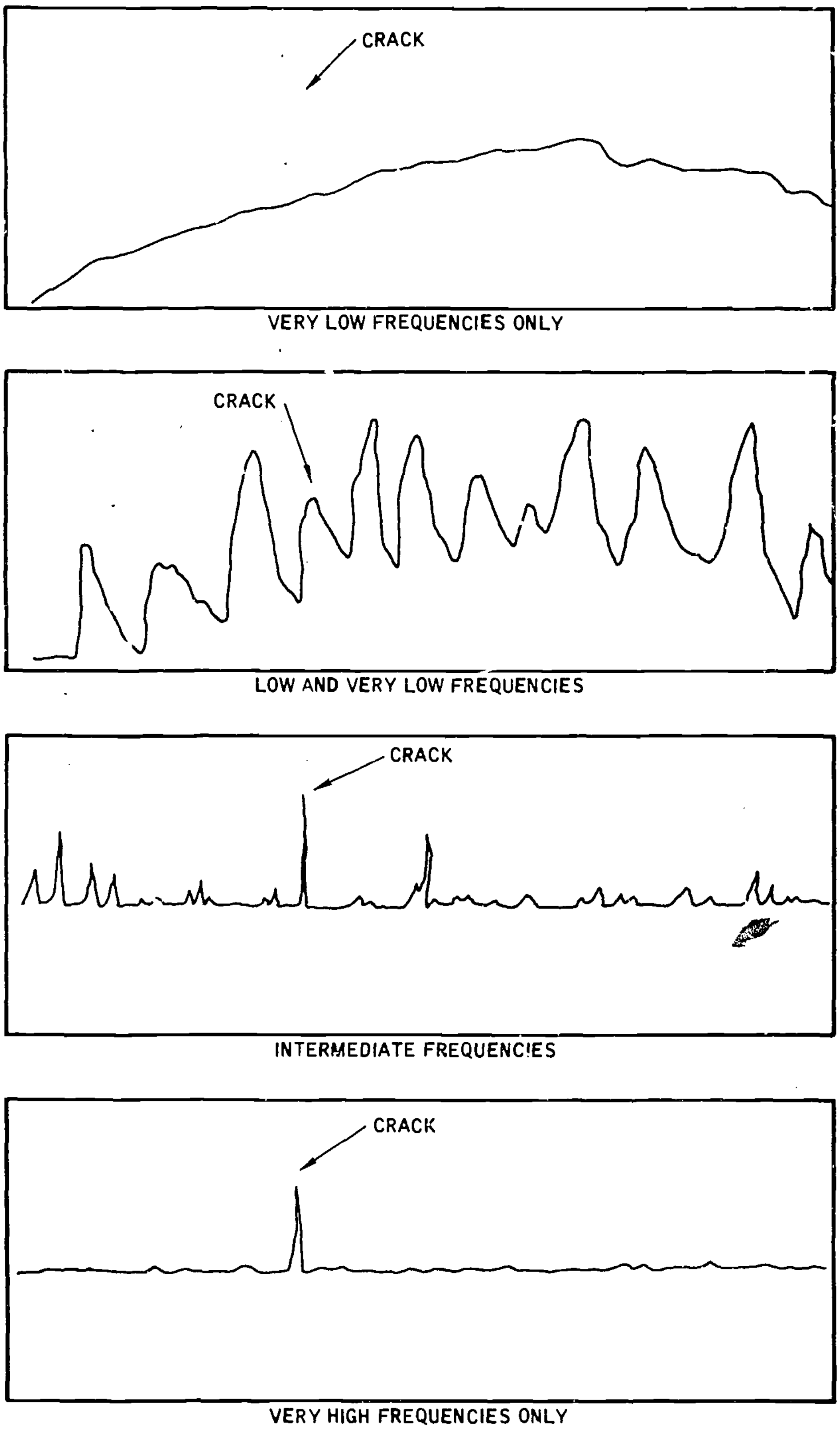


Figure 4-17. Typical Modulation Analysis Indications

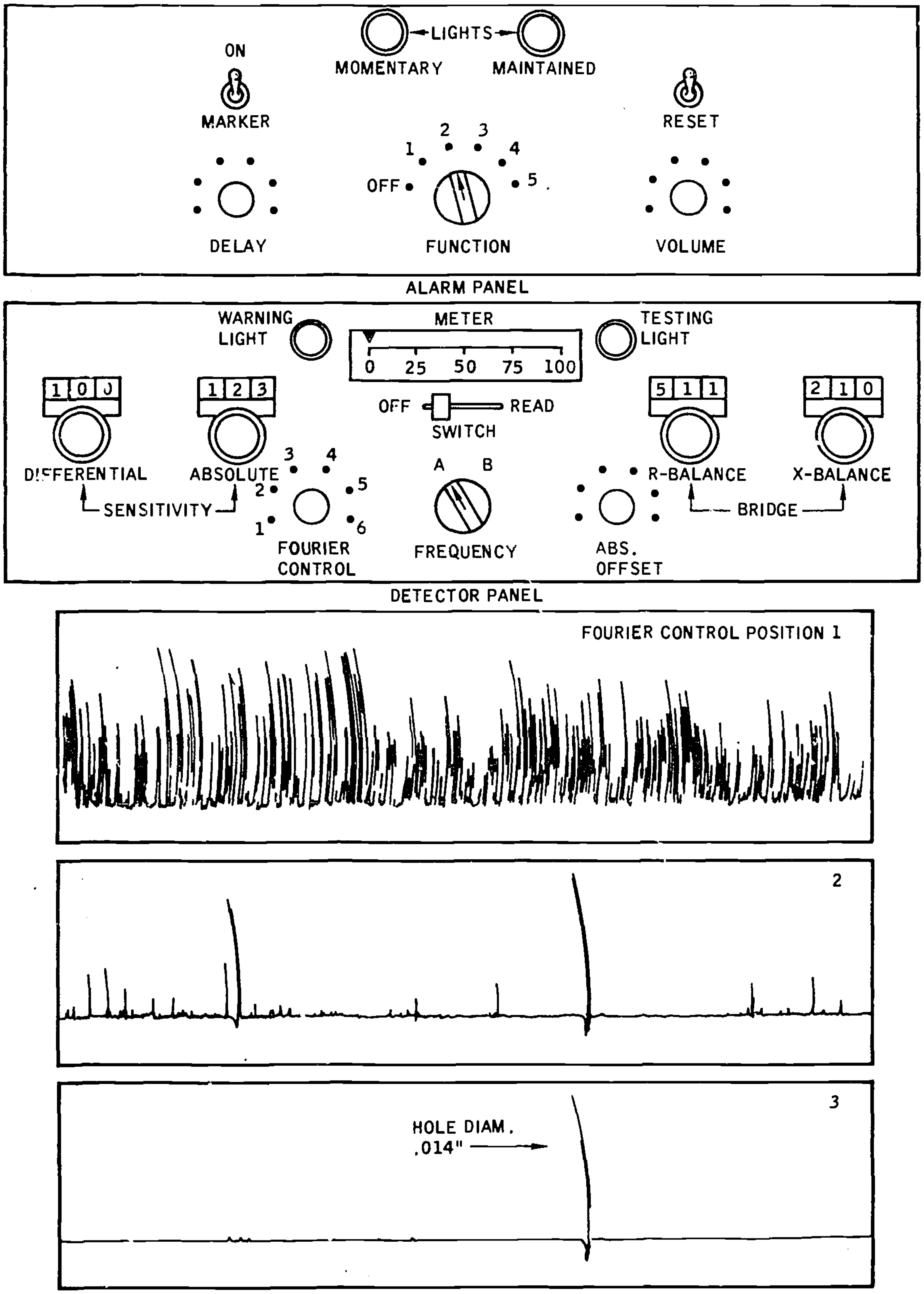


Figure 4-18. Typical Modulation Analysis Unit With Indications (Recording Section Not Shown)

2. TEST SPEED

The modulation analysis technique is based on the relative motion between the test article and the test coil. Normal movement through the test coil is from 40 to 300 feet per minute; however, higher test speeds are possible. Below 40 feet per minute, a loss in sensitivity occurs so it may not be possible to use low speeds in some applications. Use of the modulation analysis technique requires a constant speed motor to ensure that the relative motion between the article and the test coil is constant.

It should be considered that the article speed through the coil does not exceed the signal, that is, "run away" from the particular test frequency used. The article should be in the test coil long enough for the electromagnetic wave to travel in depth for the required test and return a data signal to the coil. If the article has passed the test coil before the return of the data signal, the condition is called "run away." A choice of raising test frequency or reducing article speed is necessary.

3. TEST COILS

In modulation analysis the test coil design is very important to successfully produce usable indications. Any of the basic types of coils may be used, although they are usually of the differential type. One of the differential coils can be used in an absolute technique, while both coils are used differentially to test very small areas of the article. All of the test coil factors discussed in Chapter 3 must be taken into account.

4. TEST FREQUENCY

Modulation analysis units are equipped with means of changing the test frequency. For each test situation an optimum test frequency exists. The selected frequency depends on the article's size and characteristics, the test coil, the test speed, and the specific article characteristic being tested. It is preferred in the selection of a test frequency to use the highest frequency allowable to cause greater modulating effects from a given discontinuity. Table 2-1 illustrates how the depth of eddy current penetration varies with the nature of the material and test frequency.

5. TESTING CAPABILITY

Modulation analysis is a high speed testing technique capable of providing over 120 responses per second. Discontinuities spaced 0.1 inch apart can be detected. When performing discontinuity testing, the modulation analysis technique is an area sensing form of testing. The depth and length of the discontinuity form the area of test. Since the test coil is encircling the article the width of the discontinuity around the circumference of the article does not cause much change in the output indication. Table 4-4 indicates typical areas that can be sensed by the modulation analysis technique.

Table 4-4. Typical Modulation Analysis Discontinuity Detection Areas

B.W. GAGE	WALL THICKNESS (INCHES)	DEPTH OF DISCONTINUITY (INCHES)	LENGTH OF DISCONTINUITY (INCHES)	AREA (LENGTH TIMES DEPTH)
24	0.022	0.001	0.050	0.00006
20	0.035	0.001	0.060	0.00006
18	0.049	0.002	0.060	0.0001
16	0.065	0.003	0.060	0.0002
14	0.083	0.0035	0.060	0.0002
12 AND HEAVIER	0.109 AND HEAVIER	4% OF WALL	0.060	---

6. PHASE ANALYSIS/MODULATION ANALYSIS INTERRELATIONSHIP

The technique of phase analysis is normally incorporated into modulation analysis equipment and is used to suppress certain variables. The equipment generally contains a bridge circuit, and it is possible to establish various bridge balancing conditions through the X and R controls. (See Figure 4-17.) Like the other phase analysis techniques covered in this chapter, either the dimensional variable or the conductivity variable can be suppressed in order to emphasize the variable of interest. Since the modulation analysis capability of the equipment is related to the bridge balance, this means that the phase analysis settings must be specified in addition to the modulation analysis settings.

7. MODULATION ANALYSIS TESTING

Because of equipment differences detailed testing procedures are not provided; therefore, the following discussion will present only a general approach to modulation analysis testing.

a. Calibration. Calibration is the process of setting the equipment controls in accordance with an approved procedure and by passing a reference standard through the test system. The reference standard must be an acceptance quality control standard. When calibrating the equipment the resulting indication must correspond to the indications established by the approved reference standard. An approved standard should be available for each type of article to be tested. The approved test article (standard) should be prepared with discontinuities that would represent the acceptable or unacceptable limits of the test. The reference standard should be applied to the test equipment prior to and after performing tests on a specific group of articles. This assures that the equipment remains calibrated during the entire test period.

b. Setup. In addition to performing calibration procedures, several factors are related to the task of establishing the initial conditions for test.

(1) Since modulation analysis is a moving system, special attention must be given to adjusting the rollers. The rollers must be aligned horizontally and vertically so that the article passes smoothly through the rollers without bouncing or impacting the rollers. Such conditions will cause false indications.

(2) Recording adjustments must also be made to ensure that the recorder properly reflects the output of the test coil.

(3) In addition, the marking pen must be adjusted to ensure that discontinuities are properly identified.

(4) Some modulation analysis equipment uses prepunched cards to establish the initial conditions for test. Through the use of these cards, the limits for the test are automatically established for a given test condition. This also establishes the acceptance/rejection criteria for the test. Other equipment accomplishes this same task by simple integrated controls in the equipment. The length of the discontinuity and the number of discontinuities allowed per foot can be set by the controls. This, in addition to setting the test frequency, automatically establishes the initial conditions for test.

c. Test. Since modulation analysis is a moving system, the NDT specialist's actions are generally limited to the task of ensuring that the article is passing freely through the test system. The recorder may or may not be operating, depending upon the nature of the test.

d. Interpretation. When the recorder is used, the recording results can be compared with previous results. If a significant change exists, retesting can be accomplished and, through the controls on the equipment, further analysis can be made.

e. Special Factors. Two factors merit special consideration. First, the article must always be passed through the test coil in the same direction because of the directional characteristics of some coils. And second, long seams and laps may not be detected by the encircling coil technique. This problem can be solved by the use of a rotating surface coil which scans the circumference of the article.

408 RELATING INDICATIONS TO DISCONTINUITIES

1. GENERAL

The nature of eddy currents is such that a clear relationship does not exist between the indication and the depth, size, and shape of a discontinuity within an article. In general, it is not possible to accurately visualize the discontinuity based on the output indication.

2. HOW EDDY CURRENTS SENSE A DISCONTINUITY

In discontinuity sensing, the discontinuity disrupts the normal eddy current paths within the article. The disruption varies with the depth, volume and nature of the discontinuity.

a. Test Coil's Magnetic Field Distribution Within Article. The test coil's magnetic field distribution within an article is a variable which depends upon the coil's shape, the coil's position, and the nature of the article.

   Thus the distribution is a variable and varies within an article. However, for a specific article, the distribution does form a pattern which can be used as a reference.

b. Eddy Current Paths. The paths formed by the eddy currents are directly related to the pattern formed by the coil's magnetic field. The result is an eddy current pattern which, like the coil's magnetic field, is unique to the particular testing system and test article. This eddy current pattern is used as a reference for sensing discontinuities.

3. STATIC TESTING CONDITIONS

A static testing condition can be defined as a situation in which a surface coil is located on the surface of an article and is slowly moved across the surface. The output equipment might be a simple discontinuity detector which provides an output indication in the form of a meter scale. The presence of a discontinuity will cause the indicated value on the meter to change. If no discontinuities are present, the indicated value will remain constant. When the presence of a discontinuity causes a change in the output indication, the problem arises as to the meaning of this indication change. In some cases, the answer can be found by relating the observed value to a reference standard with known discontinuities. This approach is a comparison method and provides only an approximation. No present means exists for providing exact results. At this point, one course of action would be to use another form of nondestructive testing and/or metallurgical analysis to evaluate the discontinuity.

4. DYNAMIC TESTING CONDITION

An article moving steadily through a test coil represents a typical dynamic testing condition. The output indication can be a cathode ray tube or a recording strip. Since phase and modulation testing provide the greatest amount of information, the following statements apply to this form of testing.

a. Eddy Current Pattern. As an article moves through a test coil, it is convenient to visualize the article as being tested by a small field of eddy currents within the article. This field will be affected by the presence of a discontinuity. Because the density of eddy currents varies within the article, the density of the field will not be the same across the field. The NDT technician should also realize that the output indication is related to the density of the eddy current field in the area that is intercepted by the discontinuity as well as by the size of the discontinuity.

b. Position of Discontinuity With Respect to Eddy Current Field. As the article moves through the test coil, the discontinuity may fall completely or only partially within the field due to the lack of eddy current penetration. In doing so, it should be remembered that eddy currents will flow around the discontinuity and this causes a change in the output indication.

c. Depth of Discontinuity. Figure 4-19 illustrates three indications appearing on a recording strip used in modulation analysis testing. Indications were obtained from an article with three holes having the same diameter. Based on these indications, it might be supposed that the depth of a discontinuity can be related to the output indication. In actual practice this is not true because the area, as well as the depth, of the discontinuity varies.

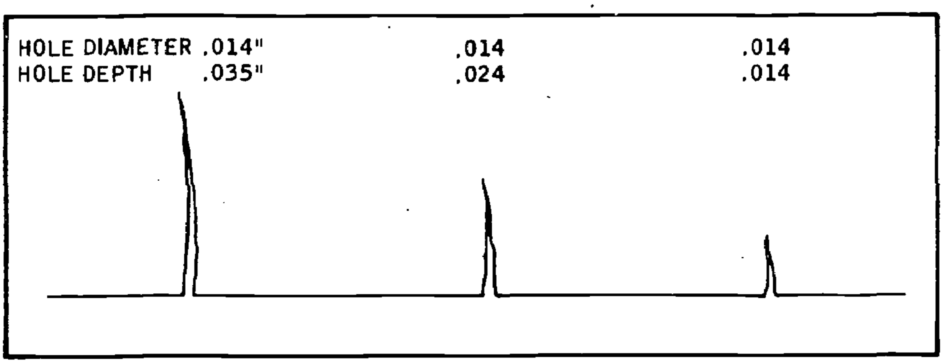


Figure 4-19. Recording Chart Showing Response to Three Number 80 Drill Holes

d. Area Sensing. In a dynamic system, eddy current testing is an area sensing system in which the area is composed of the depth and the length of the discontinuity. Since the article is moving through the coil at a steady speed, area sensing is directly related to the specific test speed and the ability of the equipment to resolve adjacent discontinuities. This resolution characteristic is a function of the specific equipment. In a typical case, three small discontinuities spaced 0.1 inches apart along a length of tube can be resolved at a test speed of 50 feet per minute. The discontinuities were 0.014 inch diameter drill holes (#80) drilled to a depth of 0.010 inches in a 1-inch, 0.109 inch wall, 304 stainless steel tube. This amounts to resolving discontinuity impulses spaced 10 milliseconds apart.

e. Phase Delay. The output indication is also affected because the electromagnetic waves will move through the conductors at different speeds. The velocity of the wave is defined by the formula $v = f\lambda$, which shows that the wave velocity decreases as the test frequency decreases or as the wavelength decreases.

f. Significance of Phase Delay. Since the article is moving through the test coil at a relatively high speed (40 to 300 feet per minute), phase delays can affect the value of the output indication. Also, discontinuities at different depths produce different phase delays. Most equipment contains phase circuits which can be adjusted for specific test conditions. Again this is a characteristic of particular test equipment and thus prevents the use of reference standards that can be applied to all eddy current testing equipment.

5. OUTPUT INDICATION

In general it can be said that the relationship between the output indication and the actual discontinuity characteristics (size, location, configuration and depth) within an article cannot be accurately visualized on the output indication. However by the use of artificial or natural reference standards and specific test equipment a qualitative comparison of the discontinuity can be made.

409 TECHNIQUES

1. GENERAL

Eddy current testing and the variables that affect eddy currents are identified in the following paragraphs.

2. EDDY CURRENT VARIABLES

A number of variables affect eddy currents. Since they change the eddy current indication, many can be measured or detected by eddy current testing. Those which affect eddy currents are listed as follows:

a. Discontinuities.

b. Article dimensions, including diameter thickness, eccentricity, and coatings, where applicable.

c. Electrical conductivity of article as affected by alloy composition, heat treatment, and effects of cold working (dislocations and orientation).

d. Internal stresses in metals.

e. Vibrations and other changes in the coupling distance between the article and the test coil during testing.

f. Noise pickup (power lines, radio and electronic interference).

g. Temperature.

3. TESTING CAPABILITIES

Eddy current testing can be applied to round, flat, and irregularly shaped conductive articles. It is also possible to measure the thickness of both conductive and nonconductive coatings. The thickness of a nonconductive article may be measured by backing the article with a conductive article and using the lift-off effect to measure the thickness of the test article. Variables that can be measured or detected by eddy current testing are:

a. Conductivity (varies with materials characteristics).

b. Hardness (conductivity changes as the hardness changes).

c. Strength (conductivity value is related to the stress characteristics of the article).

d. Heat treatment (variations in heat treatment cause variations in conductivity).

e. Dimensions (dimensional changes cause changes in lift-off or fill-factor between the article and the coil).

f. Coating thickness (differences in conductivity exist between a conductive coating and an article; nonconductive coating varies the lift-off between the coil and the conductive area of the article).

g. Discontinuities (cracks, inclusions, etc. cause changes in output indications).

h. Temperature (conductivity changes with temperature).

4. ADVANTAGES AND LIMITATIONS

Eddy current testing, like other forms of nondestructive testing, has specific advantages and limitations.

a. The main advantage of eddy current testing are:

(1) High speed testing.

(2) Accurate measurement of conductivity.

(3) Discontinuities at or near the surface of the article can be reliably detected.

(4) High sensitivity to small discontinuities.

(5) Accurate thickness measurements.

b. The main limitations of eddy current testing are:

(1) Limited penetration into article.

(2) Several variables simultaneously affect output indication.

(3) Discontinuities are qualitative, not quantitative, indications.

5. CYLINDERS

Cylinders are generally tested by using the differential coil arrangement shown in Figure 4-20. In this arrangement, the secondary coils are connected so that the output of one coil opposes the output of the other coil. If the conditions in the area under each coil are the same, no output indication exists.

a. Assumptions. In using the differential coil arrangement it is assumed that discontinuities do not extend over both coils.

b. Small Discontinuity. The appearance of a small discontinuity under one coil generates an unbalanced condition between the two coils and an output indication will exist.

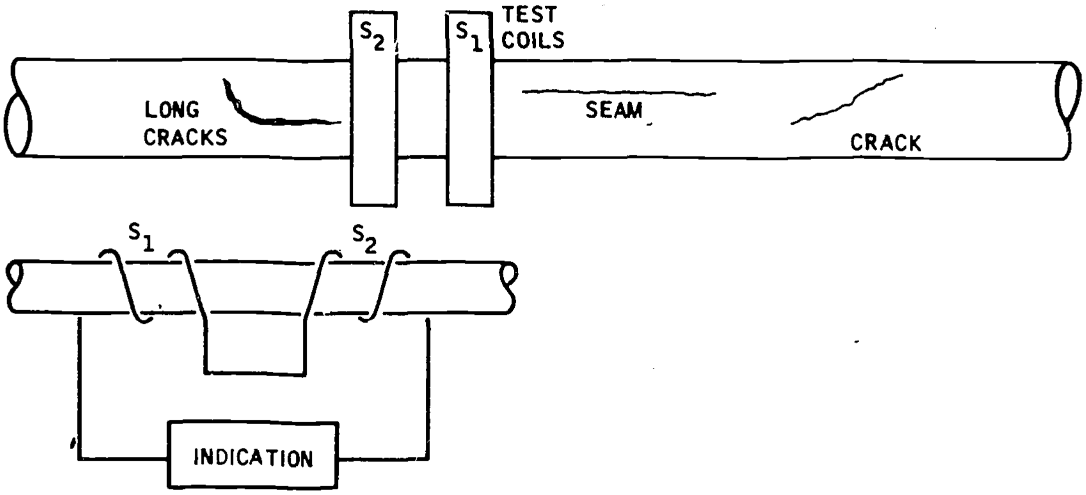


Figure 4-20. Differential Coil Arrangement for Cylinder Testing

c. Location of Discontinuity on Circumference. When the encircling coil arrangement is used, it is not possible to determine the position of the discontinuity on the circumference of a cylinder. A surface coil can be used to locate the position of the discontinuity on the circumference.

d. Seam Parallel to Surface. A long seam parallel to the cylinder's surface cannot be detected by the differential coil arrangement because the seam extends under both coils and is oriented in the same way. Since no difference exists, no output indication will be obtained.

e. Long Discontinuity Perpendicular and Parallel to the Surface. A long discontinuity (crack) may extend under both test coils. Since the discontinuity is both perpendicular and parallel to the surface, each test coil will produce a different output. Under this condition, an output indication can be obtained even though the discontinuity extends under both coils.

f. Conductivity Measurements. Since the conductivity of one area of the cylinder is being compared with the conductivity of another area of the cylinder, differences in conductivity can be obtained.

g. Dimensional Changes. When dimension is the variable of interest, it is possible to adjust the system so that dimension differences can be detected.

h. Saturation. Direct current saturation coils must be used when permeability effects must be cancelled.

i. Depth of Testing. Since the depth of eddy current penetration depends upon the test frequency, the cylinder's conductivity and permeability, the NDT specialist must realize that the depth of testing depends upon the specific conditions.

j. Fill-Factor. The diameters of the test coil and the cylinder determine the fill-factor for a specific test application. To ensure consistent testing, the proper test coil must be used with a specific cylinder under test.

k. Roller Adjustments. To minimize the generation of additional variables and to ensure consistent testing, the rollers that position and guide the cylinder through the test coil must be carefully adjusted.

l. Reference Standards. A cylinder which has been previously tested and established as a reference standard is passed through the test system to ensure proper adjustment and performance of the system.

m. Center of a Cylinder. The NDT specialist should realize that eddy currents are not developed at the center of the cylinder; therefore, discontinuities cannot be detected in this area.

n. Sensitivity to Discontinuity Orientation. Discontinuities may be oriented circumferentially (parallel to the circumference) or axially (from the center to the surface). Since the direction of the eddy current parallels the current flowing through the test coil, maximum sensitivity is oriented towards axially oriented discontinuities. The encircling coil system is, therefore, relatively insensitive to circumferentially oriented discontinuities.

6. TUBING

Much of what has been stated about cylinders also applies to tubing. Testing of tubing, however, presents unique problems.

a. Wall Thickness. The wall thickness is the key factor in applying eddy current testing to tubing. This thickness may be greater than the depth of eddy current penetration or it may be less. If the wall thickness is greater than the depth of penetration, inside test coils may be used to complete the testing of the tubing wall. 100% testing is possible with a single coil where the wall thickness does not exceed depth of penetration.

b. Diameter Testing. In tubing the diameter may be the variable of interest, rather than wall thickness. Through phase control adjustments, it is possible to suppress the wall thickness variable (conductivity) and emphasize the dimensional changes of the tubing's diameter.

c. Location of Discontinuity on Circumference. When the encircling coil arrangement is used, it is not possible to determine the position of the discontinuity on the circumference of a tube. A surface coil can be used to locate the position of the discontinuity on the circumference.

d. Seam Parallel to Surface. A long seam parallel to the tubing's surface cannot be detected by the differential coil arrangement because the seam extends under both coils and is oriented in the same way. Since no difference exists, no output indication will be obtained.

e. Long Discontinuity Perpendicular and Parallel to the Surface. A long discontinuity (crack) may extend under both test coils. Since the discontinuity is both perpendicular and parallel to the surface, each test coil will produce a different output. Under this condition, an output indication can be obtained even though the discontinuity extends under both coils.

f. Conductivity Measurements. Since the conductivity of one area of the tube is being compared with the conductivity of another area of the tube, differences in conductivity can be obtained.

g. Saturation. Direct current saturation coils must be used when permeability effects must be cancelled.

h. Fill-Factor. The diameters of the test coil and the tube determine the fill-factor for a specific test application. To ensure consistent testing, the proper test coil must be used for the specific tube under test.

i. Roller Adjustments. To minimize the generation of additional variables and to ensure consistent testing, the rollers that position and guide the tube through the test coil must be carefully adjusted.

j. Reference Standards. A tube which has been previously tested and established as a reference standard must be used to ensure proper adjustment and performance of the system.

k. Sensitivity to Discontinuity Orientation. Discontinuities may be oriented circumferentially (parallel to the circumference) or axially (from the center to the surface). Since the direction of the eddy current parallels the current flowing through the test coil, maximum sensitivity is oriented towards axially oriented discontinuities. The encircling coil system is, therefore, relatively insensitive to circumferentially oriented discontinuities.

1. Corrosion Testing. Since eddy current testing is basically a near-surface testing system, sensitivity is greatest at or near the surface. In tubing, corrosion may be located on the inner or outer surface and therefore be detected by eddy currents.

7. SHEETS

Sheets (or plates) are tested for material properties, discontinuities, and thickness. Testing can be accomplished manually or automatically. In some instances, flat-type encircling coils can be used and the sheeting can be automatically passed through the coil's slot. For most cases, use of a surface coil is required. Again, this can be automated to provide scanning. Like thin-walled tubing, thickness can be accurately measured, using the conductivity properties of the material.

8. IRREGULAR ARTICLES

Irregular articles can be tested by comparing specific areas on the test article against identical areas on a reference standard. Special fixtures are often used to ensure that positioning of the surface coil is standardized in specific areas.

9. COATINGS

As previously pointed out in this chapter eddy current testing provides a means of measuring the thickness of coatings (or platings) on articles. This applies to cylinders and tubing, as well as to sheets. The coating may be either conductive or nonconductive. Depending upon the nature of the coating, either conductivity or lift-off is used to perform the test. Special equipment can be used to indicate thickness directly in terms of physical units of measurement. An alternative is the use of curves which relate indications to physical units of measurement.

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CHAPTER 5: EDDY CURRENT METHOD CONTROL AND TEST SYSTEM DEVELOPMENT

500 GENERAL

Eddy current testing equipment requires method control for maximum sensitivity. In some cases this can be very simple, such as a specially designed jig, coil or probe. In other applications it might be handling and feeding equipment to control certain variables.

Since you will use nondestructive testing to improve the structural confidence level, it is desirable to build reliability into the nondestructive testing systems. This does not necessarily involve extreme complexity. In many instances it can be kept very simple. Be sure the entire system is suited to the test to be performed. Very little is accomplished, for example, if the eddy current equipment used to test cylinders is speed sensitive and the conveying or driving apparatus permits wide speed variations. The basic elements of the eddy current testing system are the coil or sensing unit, the generator, and the indicator. Normally the generator and the indicator may be considered a piece of standard equipment. Which leaves the coil as the element of primary interest. Coils are usually developed for a particular function by selecting a material and coil parameters that will match a particular generator which is to be used.

501 COIL PARAMETERS

1. GENERAL

The theory behind coil design is very complex, therefore, only a limited coverage of this subject will be presented. Actually, the design, choice, and application is more of an art than a science since in many cases, the NDT specialist involved is not aware of problems caused by certain variables until testing has actually begun. Further, it is very difficult, if not impossible, to predict what conditions are present in the test article and how they will influence test system response.

Through building and testing of probes or coils, knowledge of eddy currents and their application may be acquired. By observing the test results, the NDT specialist will be able to learn many of the characteristics of properly and/or improperly designed probes or coils.

2. PROBE SIZE

One of the major faults in eddy current testing is the use of an over-size probe. The probe coil should be no greater than twice the length of the minimum discontinuity of interest.

3. FIELD SPREAD

It also must be realized that the eddy current field in a probe will be confined to an area approximately equal to the diameter of the probe coil. This would mean that in eddy currents the field spread is negligible.

4. FILL FACTOR

When designing an inside or encircling coil the "fill factor" (ID of coil to OD of article or vice versa) is the primary consideration.

5. WINDING

In the design of the test probe or coil the actual winding should be as close to the area of interest as possible so that the area will receive the strongest eddy current field.

6. TYPE OF MOUNTING

The type of mounting material for the probe or coil does not have to be elaborate. A well insulated stiff, nonconductor which will support or hold the coil firmly against or around the article is sufficient.

7. WIRE GAUGE

The wire gauge should be no smaller than number 36 (.005). A larger size is permissible.

8. NUMBER OF TURNS

The exact number of turns for best results depends on the application. Several examples are:

a. Coil. For an article 3/8 inch diameter or less, approximately 50 turns for the coil wound to fit the article. For articles 3/8 to 1 inch diameter, about 35 turns for the coil. The coils may be wound (using the same number of turns) either with a short axial length, and large radial build-up to spread out the eddy currents, or the coils may be wound with a long axial length and small radial build-up to test only a small area, depending on the particular application.

b. Probe. General purpose probe; pancake 1/8 inch thick (axial dimension) wound on a 1/8 inch diameter nonconductive rod with 190 turns of number 35 gauge enameled wire. This type can be used on magnetic or nonmagnetic metals.

c. Inside Coil. Pancake 1/8 inch thick (axial dimension) wound on a 0.090 inch diameter ferrite core 5/32 inch long with 140 turns of number 36 gauge enameled wire. Ferrite cores are used primarily to make a small coil diameter possible.

9. EVALUATION

To determine that the proper number of coil wire turns were used check the coil in the following manner:

a. Place the object being tested fully within the coil, the meter indicator pointer should read on-scale for any "Frequency" control setting after making "Balance" and "Lift-off" control adjustments at maximum sensitivity.

b. If these conditions cannot be met, remove several turns and try again.

502 SYSTEMS DEVELOPMENT

1. GENERAL

Many types of test systems are available. Although most test systems are basically impedance bridges of one form or another, they come in a variety of sizes, shapes, and designs. Some systems are used only for magnetic materials, others for non-magnetic materials. Some systems use probe coils, others encircling or inside coils, while still others are designed for use on a variety of materials and use both probe and encircling coils.

The question arises as to how the engineer or NDT specialist chooses the proper test system. Perhaps the clearest way to show the process involved in system development is to present and then solve typical test problems.

2. THE SEPARATION OF IMPROPERLY QUENCHED MOLYDENUM-CHROMIUM-VANADIUM STEEL CYLINDERS

a. Statement of Problem. A number of 25/32 inch diameter cylinders ruptured during dynamic pressure testing. Failure analysis disclosed that the failure was metallurgical in nature and not mechanical being attributed to improper heat treat with a resulting grain structure of ferrite, bainite and some martensite. The latter causing the failure when the cylinder was subjected to dynamic pressure testing.

Since large volumes of these cylinders were in stock and no positive means of identification as to heat, each would require some type of testing to identify heat treat status. The solution required a rapid, economical means of nondestructively screening the properly heated cylinders from improperly heat treated.

b. NDT Analysis.

(1) The material in question was magnetic.

(2) Heat treatment will change the permeability and conductivity properties in magnetic materials, the change depends upon the stage of heat treat.

(3) Eddy currents can separate and evaluate permeability and conductivity changes.

(4) The effect of improper quenching is a gradual change and will not behave like a localized discontinuity; therefore, not requiring 100% coverage of the questionable articles.

c. NDT Procedure.

(1) Reference Standard. Select a properly quenched tube for the reference standard (tube) and verify metallographically for 100% martensitic microstructure.

(2) Eddy Current System Selection. Differential encircling coil system was selected with a test frequency of 60 cps or less for magnetic material. The field strength was 25 to 75 oersteds. This was determined by obtaining normal induction curves from the articles representing improper quench and properly quenched articles. If such curves are not available, a series of trial and error tests must be conducted to resolve the difference between the articles by varying the field strength.

d. Readout. Readout in this case could be on either a meter or an oscilloscope (CRT). Figure 5-1 shows the CRT wave pattern for a properly quenched tube (view A) and improperly quenched tube (view B). With a meter, an improperly quenched tube would be indicated by a needle deflection away from zero (Figure 5-2).

e. Summary. Several observations could be drawn from this problem. Since the article was magnetic both permeability and conductivity would vary according to the heat treat. An improper quench would lower conductivity by increasing the permeability (opening of hysteresis loop). This loss would result in a different voltage being developed across the secondary of a coil encircling the tubes with correct and incorrect quenching. The output from the secondary of the test coil would be bucked against the secondary voltage obtained from a reference coil containing a 100 percent martensitic,

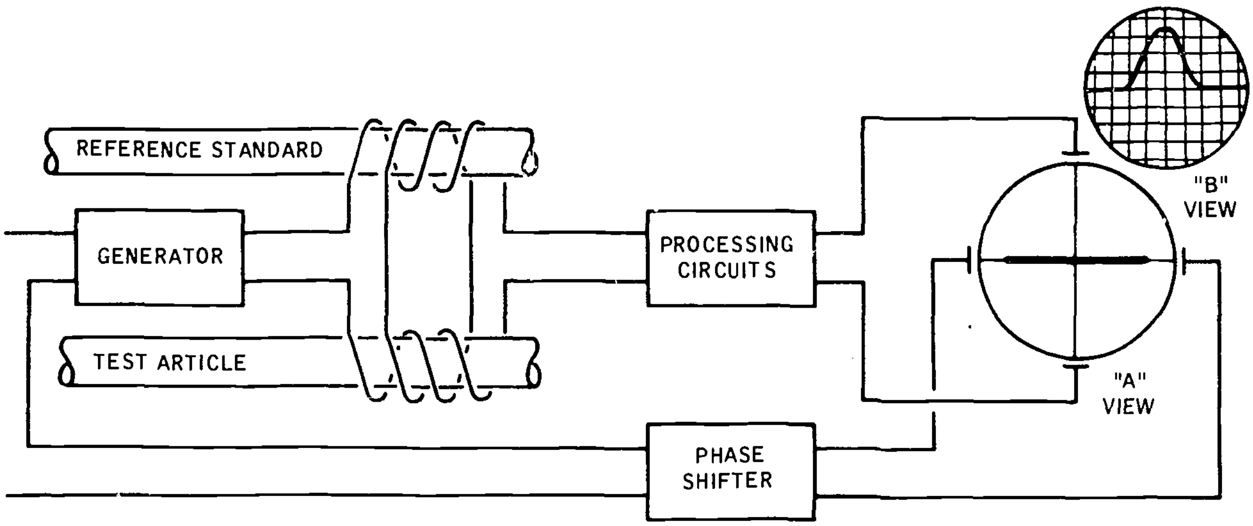

Figure 5-1. CRT Presentation

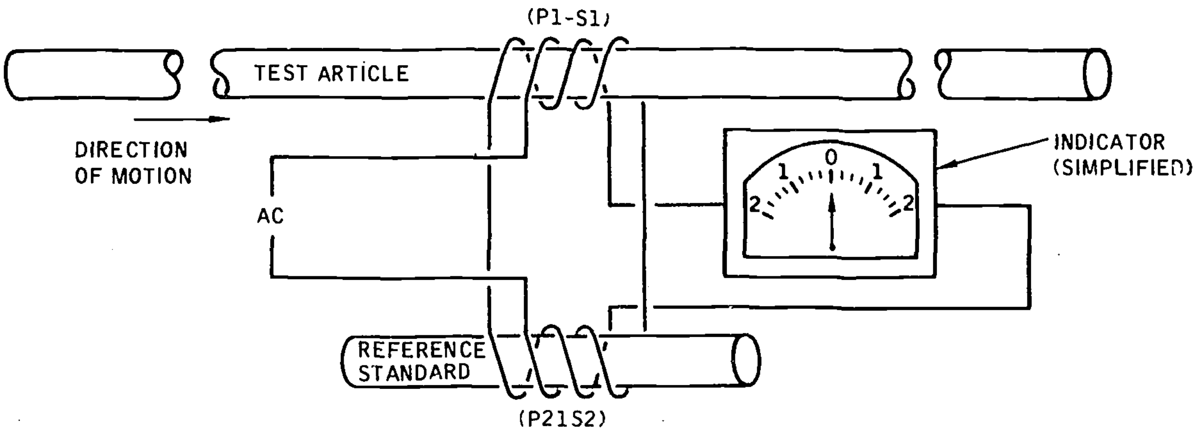

Figure 5-2. Meter Presentation

properly quenched tube, and the difference between these two voltages would be amplified and displayed in the readout sub-system. The displayed voltage, therefore, could be related to the metallurgical difference between the test tube and the reference standard.

3. SEPARATION OF IMPROPERLY WELDED TITANIUM PRESSURE VESSELS

In many cases the solution to a problem may not require designing a special coil. Often it is only necessary to prepare a representative standard. Such was the case in the following problem:

a. Statement of Problem. During the fabrication of a group of titanium alloy, Ti-6Al-4V, pressure vessels, an unauthorized change in welding procedure resulted in a number of the vessels being welded with commercially pure titanium weld wire which caused embrittled weldments. The records were not sufficient to determine which vessels were properly welded and which were improperly welded. Therefore, it was necessary to develop nondestructive testing procedure for sorting the good and bad vessels.

A study of the welding process revealed that at some point in the fabrication of the pressure vessels, the approved Ti-6Al-4V welding wire was replaced with a commerically pure titanium wire. Since these alloys differ in conductivity by a ratio of 3:1 (commercial pure titanium versus alloy titanium), an eddy current test was selected as the most promising NDT tool.

b. NDT Analysis

(1) Weld material is nonmagnetic.

(2) Impedance (surface probe) method should be used.

(3) There is considerable difference in electrical conductivity of the two filler wires used.

(4) Representative standards of the two welds must be prepared.

c. NDT Procedure

(1) Standard welds were prepared, using each type of wire.

(2) A variable frequency eddy current instrument was selected for the test.

(3) The standard probe, supplied with the instrument, and a frequency of approximately 30 kcps were used.

(4) The sensitivity and balance of the instrument were adjusted to give a minimum on-scale reading when the probe was placed on the weld made with the Ti-6Al-4V. When the probe (coil) was then placed on the weld made with the pure titanium wire, the instrument gave a full scale deflection, Figure 5-3.

(5) The suspect welds were then tested, with any large, up-scale deflection being considered sufficient for pinpointing the discrepant welds.

d. Summary. Several meter readings were taken at various locations on each vessel to eliminate the possibility that the coil may be detecting a crack and therefore giving a low scale deflection whereby the commercially pure titanium welds could be mistaken for alloy weldments.

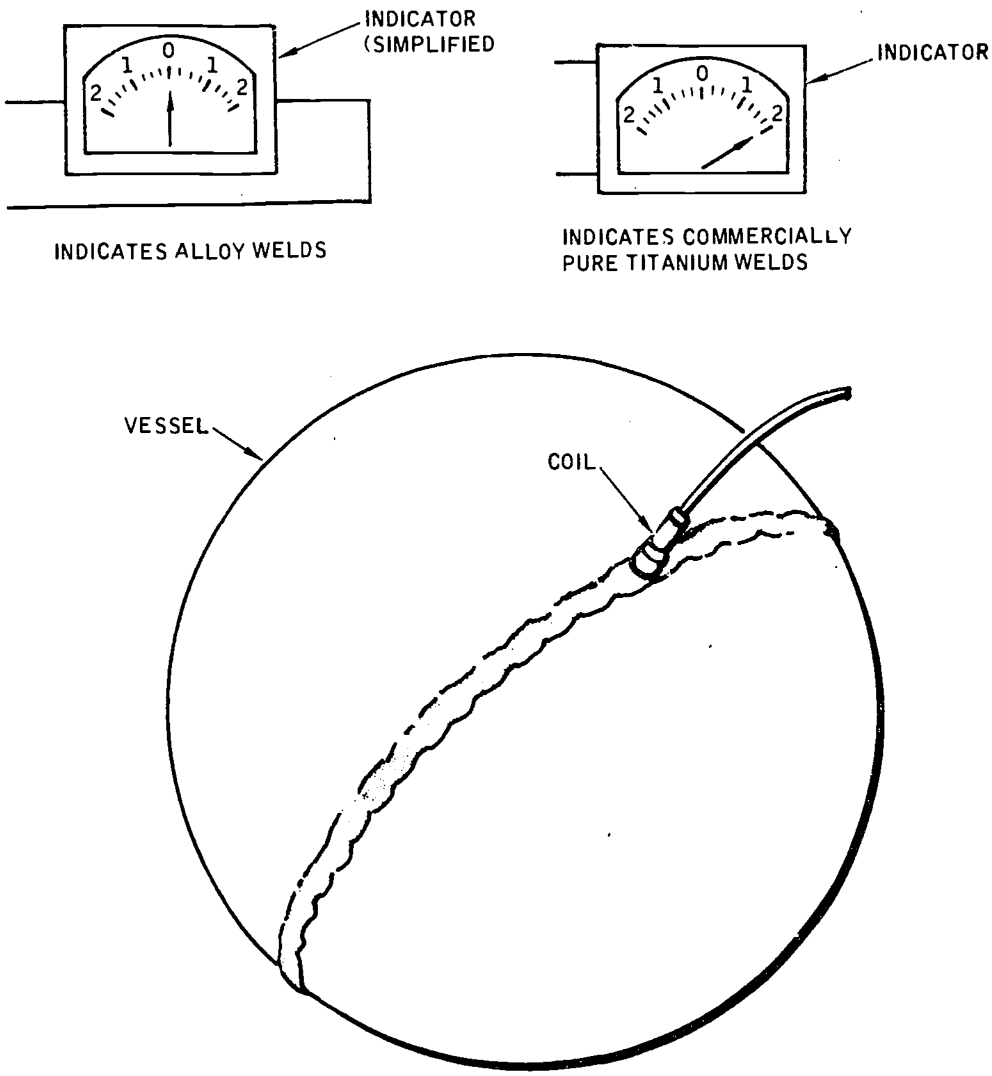

Figure 5-3. Titanium Pressure Vessel

4. DETECTION OF GRINDING CRACKS IN VALVE ASSEMBLY

a. Statement of Problem. Grinding cracks in a valve subassembly did not permit a seal to be made. The material was special X-200 steel with a magnetic permeability of 169 in the annealed condition and an electrical resistivity of 40 micro-ohm-cm. The part was a 4" cube with four 3/8" diameter holes extending 2" into the material (Figure 5-4). The 3/8" diameter holes were finished with a grinding operation which became the origin of the grinding cracks. All articles that contain grinding cracks are questionable.

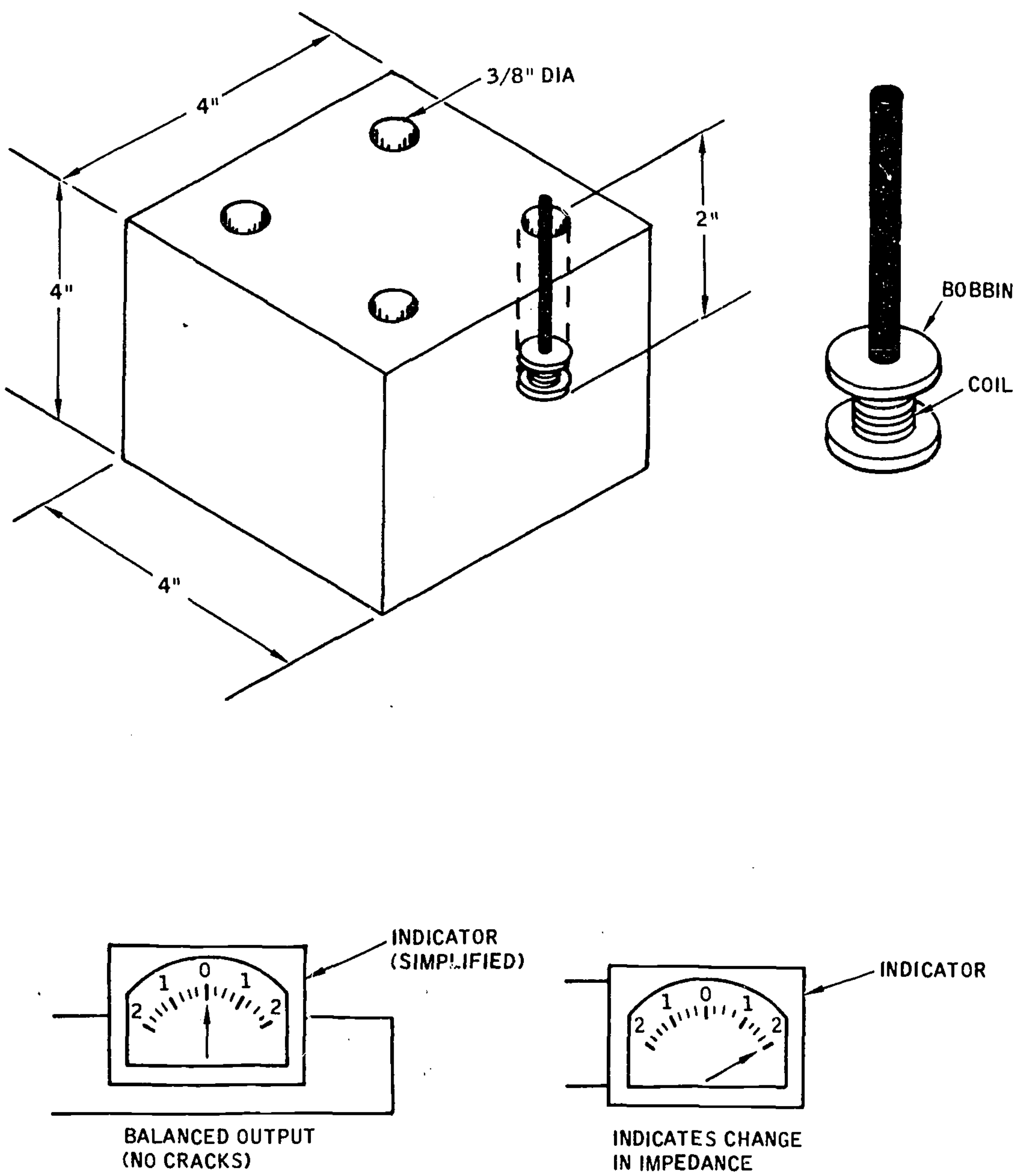

Figure 5-4. Valve Assembly

b. NDT Analysis

(1) Grinding cracks are surface cracks and in this particular problem will only lend themselves to detection by eddy currents.

(2) The length of the expected cracks will be .0005 inch to .005 inch.

(3) The material is ferromagnetic.

(4) The material has a relatively low conductivity.

c. NDT Procedure

(1) Due to the high resistivity of the material and the desired test depth a relatively high frequency may be used. For this problem, a frequency of 20 kcps was used.

(2) An inside absolute type of coil must be used.

(3) Since the material had a high permeability, an encircling dc coil was used to provide magnetic saturation. The dc coil design is not critical; however, the field must be strong enough to provide saturation. The saturation point was taken from a B and H curve for X-200 steel.

(4) The coil was wound with 50 turns of number 36 gauge magnet wire. After winding the coil was checked for compatibility with the test instrument. This was performed by connecting the coil with the instrument and by balance and "lift-off," determine if the meter remained on the scale. For procedure, refer to paragraph 501.9.

(5) A reference standard was developed using a simulated sample with known grinding cracks.

(6) The part was tested by inserting the coil into the holes and sliding the coil along the entire length of the hole while monitoring the meter for a change in out-put indication. Changes in the output indication indicated grinding cracks and the article is questionable.

d. Summary. Once a system of this type has been set up and calibrated, rapid testing may be performed. Since several parts were to be tested, periodic checks for system drift were made with the standard. Eddy currents in this case provided 100% nondestructive testing where only destructive sampling was previously possible.

503 SUMMARY

The use of electromagnetic waves for nondestructive testing outdates even the experimental proof of the reality of these waves. There is no doubt that the electromagnetic method tends to respond sensitively to almost every type of physical change in metals. The extreme sensitivity of the induction balance to many different types of variables, including breathing near the coils, is particularly illustrative. This characteristic, unfortunately, has been the source of its greatest difficulty. It was and still is, sensitive to many variables other than the one being studied, the result being that the electromagnetic method, not unlike other methods of nondestructive testing, has not always been quantitative in response. Efforts today are pointed towards developments in this area.

The phase sensitive method analysis and multiple-frequency techniques have been developed. Significant improvements have also resulted from specialized coil design. Transistorized electromagnetic equipment has resulted in the production of highly complex long trouble free lifetimes, as well as miniaturized highly portable apparatus.

Currently, eddy current testing has been developed to the stage where it provides rapid, accurate, and reproducible nondestructive testing. It is compatible with electronic control circuits and, therefore, suited to automatic or semi-automatic testing on production lines. It has speeded up certain types of tests formerly performed manually and in some cases has offered 100% nondestructive testing, where only destructive sampling was previously possible. The preceding examples of eddy current applications indicate the diversity of this field.

The NDT specialist will be concerned primarily with the testing of hardware but in some cases may participate in the design and development of highly complex systems.

The eddy current method should only be used where applicable and not looked upon as a solution to every NDT problem. The NDT specialist who wishes to expand his knowledge of eddy currents and their application will find ample additional information presented in NDT handbooks, journals and reports.

CHAPTER 6: SPECIAL APPLICATIONS
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CHAPTER 6: SPECIAL APPLICATIONS

600 GENERAL

Due to rapid technological advances in the space industry, there is an increasing need for the development of methods whereby specific types of information can be monitored and obtained. Eddy currents have become one of the major tools for obtaining data on an operating vehicle. A variety of techniques using the favorable characteristics of eddy currents have been developed. Since eddy current testing does not require physical contact with the article, measurements can be made in hostile environments such as extremely high temperatures, cryogenic temperatures, high pressures, or in any electrically conductive media. Future applications of eddy current may actually take place in space or under simulated space conditions, i.e., vacuum, high and low temperatures, etc.

This chapter is intended to stimulate interest in eddy current applications so that similar creativity may be applied to the solution of like problems.

601 DIMENSION MEASUREMENTS

1. NON-CONTACTING

One of the main advantages of eddy current testing is that an air gap can be used as the couplant between the probe and the article. This advantage permits the development of a wide range of tests which were not previously possible.

Where the environment is hostile, such as radioactive, high temperature, high pressure, vacuum or ultra low temperature, the test coils can be constructed from special materials and operated remotely.

Figure 6-1 illustrates the use of eddy currents to monitor movements in the order of 5×10^{-6} inches.

Figure 6-2 illustrates the use of eddy currents in a radioactive, high temperature environment.

2. NONCONDUCTIVE THICKNESS MEASUREMENTS

Space and aerospace applications have required the use of numerous nonconductive coatings. These coatings may range from micro films to macro deposits.

The use of eddy current testing is being universally used as a nondestructive means for controlling these thicknesses.

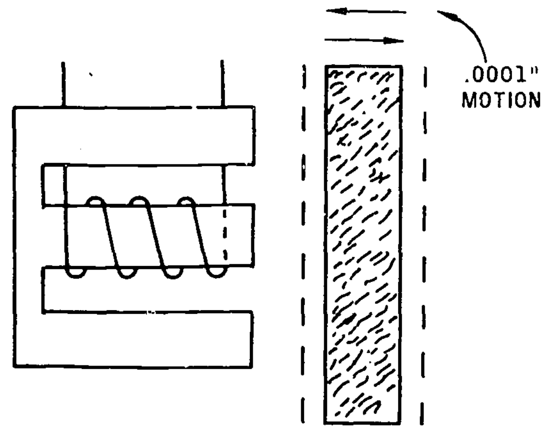


Figure 6-1. Measurement of Small Movement

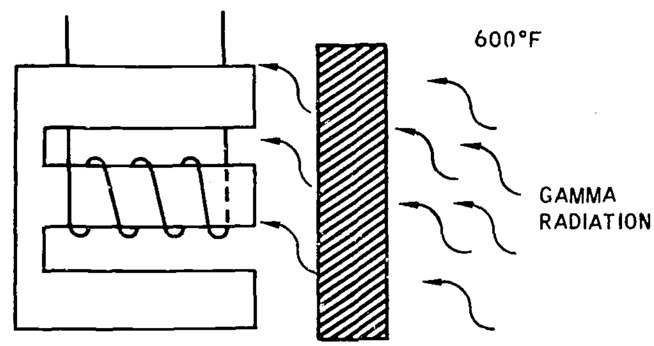


Figure 6-2. Eddy Current Measurement in Radioactive Environment

Such coatings may be produced by vacuum or electroplating, spraying, dipping, cladding, etc.

a. Micro Coatings. Figure 6-3 illustrates a very thin coating of a nonconductive material backed by a conductive or magnetic material. Since eddy current measurement is primarily lift-off, a high degree of accuracy is possible.

b. Macro Coatings. Figure 6-4 illustrates the measurement of a thick nonconductive material by backing with a conductive or magnetic material. Thicknesses up to 3 inches can be successfully measured; thicknesses greater than this are unreliable due to fall-off of the magnetic field.

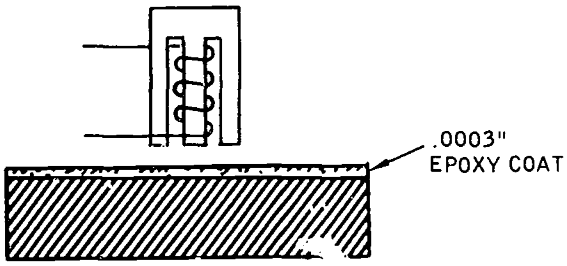


Figure 6-3. Measuring Thin Nonconductive Coatings

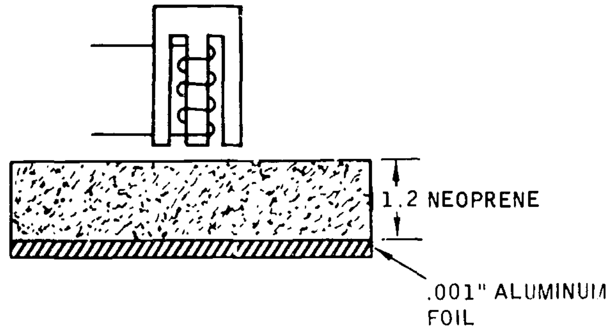


Figure 6-4. Measurment of Thick Nonconductive Coatings

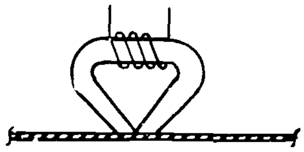
602 CONDUCTIVITY MEASUREMENTS

1. THIN MATERIALS

As discussed in Chapter 4, one of the more common uses of eddy current testing is in the measurement of conductivity. However, conductivity in thin gauges (.010 inches and less) is exceedingly difficult to measure because the measurement becomes sensitive to dimension changes when the depth of field penetration exceeds the thickness of the material.

Figure 6-5, View A, illustrates a commonly used method for measuring the conductivity of materials. In this case, however, the depth of penetration probably exceeds the material thickness thus giving an inaccurate conductivity measurement.

View B illustrates a two coil method for measuring the conductivity of extremely thin gauges of material. The two coils can be balanced out against a standard, similar to the differential coil technique. Once this is accomplished the accurate measurement of conductivity in other gauges of material is possible. The only disadvantage to this method is the need for access to both sides of the material.



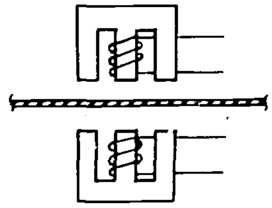


Figure 6-5. Measuring Thickness of Thin Materials

2. WELDING QUALITY CONTROL

For years other methods of nondestructive testing have been used successfully to determine weld quality. However, in each situation the weld article must be cooled to ambient temperature before testing.

In eddy current testing the coil does not have to be in contact with the article. This enables the design of a system in which the weld quality can be monitored while cooling. The only limitation is the thickness of the weld.

Figure 6-6 illustrates a typical eddy current coil designed for evaluating weldments.

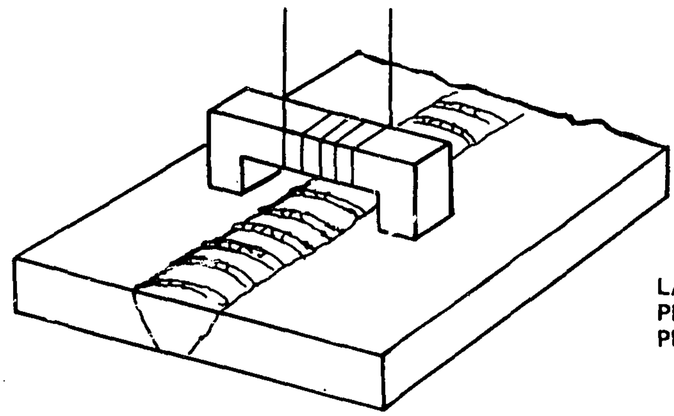


Figure 6-6. Eddy Current Testing of Welds

603 EDGE DISCONTINUITY DETECTION

1. EDGE LOCATIONS

The detection of discontinuities or measurement of properties along the edge of an article has always presented difficulty in eddy current testing due to the edge effects.

However, a shaped probe coil which rides on the lip or edge of the article (Figure 6-7) in a fixed relation to the edge, can detect discontinuities in the article since the edge effect would be constant.

2. INSIDE HOLE LOCATION

Discontinuity detection within holes can become very difficult especially when the location of the discontinuity must be determined.

Figure 6-8 illustrates an eddy current probe designed to swept circularly within the hole. This type of unit detects and locates the discontinuity within the opening.

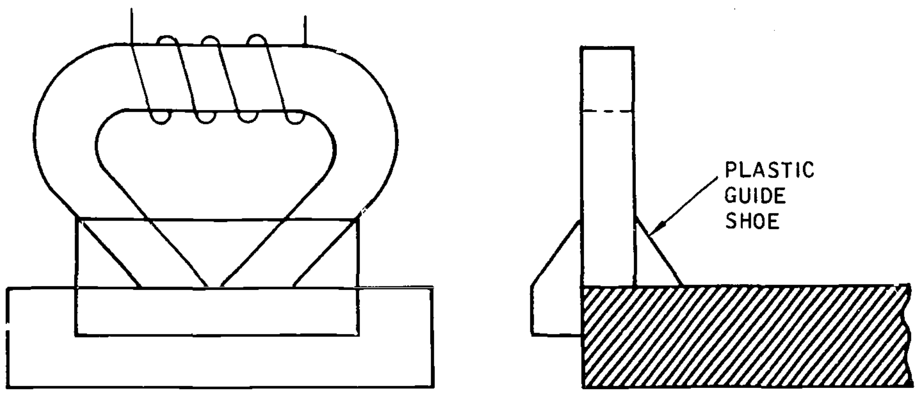


Figure 6-7. Testing for Discontinuities at Edge of Article

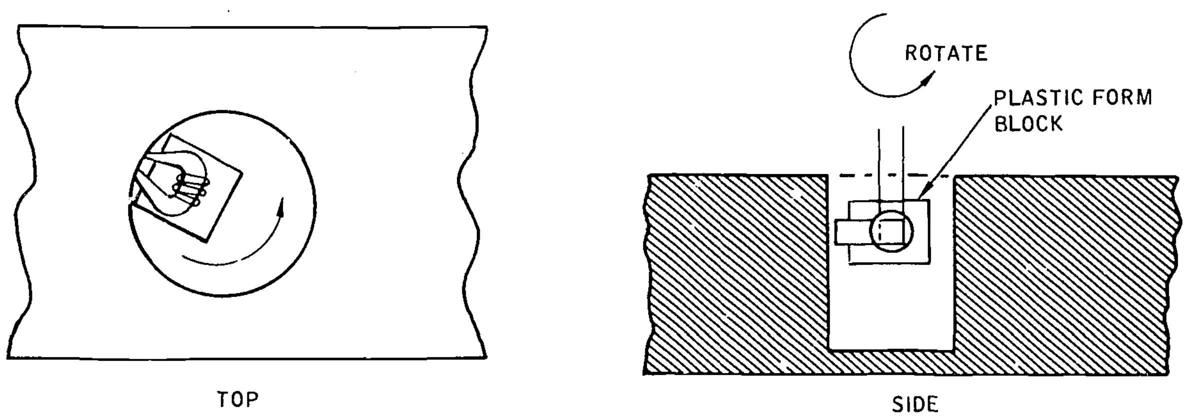


Figure 6-8. Testing for Discontinuities Inside Hole

3. MAGNETIC AND NONMAGNETIC ARTICLES

It should be realized that eddy current testing of conductive, nonmagnetic articles for discontinuities is fairly straight forward. However, detection of discontinuities in magnetic articles can be very difficult as the permeability will mask measurements. The permeability effect can be reduced by a steady state magnetic field. This magnetic field can be provided by a wire wound coil energized by direct current, or it may be sufficient to use a permanent magnet shaped to cover the small area of the article under test. (Figure 6-9.)

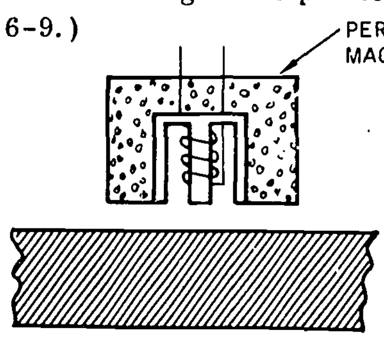


Figure 6-9. Use of Magnetic Field to Overcome Effects of Permeability

604 END-EFFECT

End effects are so pronounced that they can often be used to detect movements, make measurements, count articles, etc. You will note in Figure 6-10 how the spoke breaks the field as the wheel rotates. This produces the desired end-effect. If such a wheel were mounted within the flow of a liquid, the wheel would rotate in direct proportion to the liquid flow.

The reaction of the spokes on the probe outside the container continuously indicates the number of rotations of the wheel. The speed of rotation measures the flow. Electronic integrating counters can measure the liquid passing the measuring point.

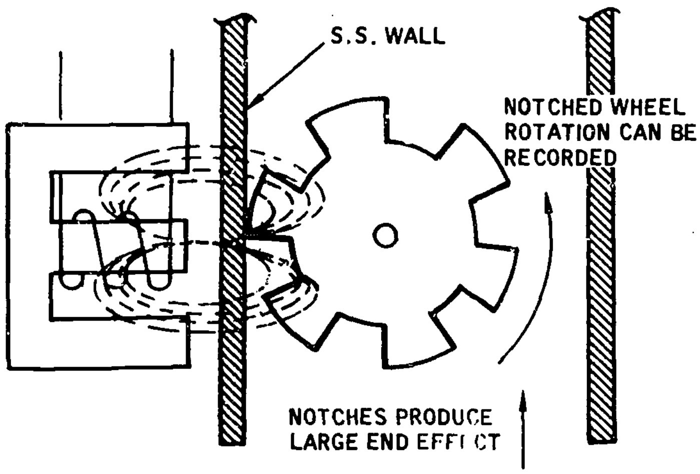


Figure 6-10. Notched Wheel Counter to Record Liquid Flow

605 LOW CONDUCTION MATERIAL

Graphite and certain other semiconductor materials present a problem in measurement of resistivity and purity; however, by proper coil design and experimentation, it is possible to assign values to these materials. Measurement by eddy current techniques removes the necessity for contact with the material and eliminates self heating. By proper design of the test coil, extremely small areas can be evaluated; however, the frequency should be high so that the magnetic field does not completely penetrate the article.

606 CONDUCTIVE LIQUIDS

The problem of measurements of liquids may be one of nondestructive testing, and will be briefly discussed. Those liquids which conduct electrons can be measured by eddy current.

1. CONCENTRATION OF LIQUID

The ability of a liquid to conduct electrons is a function of its conductivity and concentration. In a given test area we can measure this conductivity and use this information as an indication of concentration. Figure 6-11 illustrates such a test.

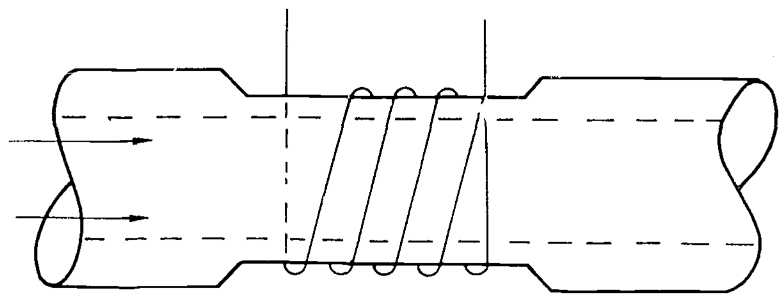


Figure 6-11. Nonconductive Pipe Section in Liquid Flow Stream

2. FLUID LEVEL

Eddy current can be used to penetrate a container and observe the level of conductive fluids. This measurement can be made even under conditions of high temperature or high pressure in the liquid environment. Figure 6-12 illustrates the measurement of fluid level.

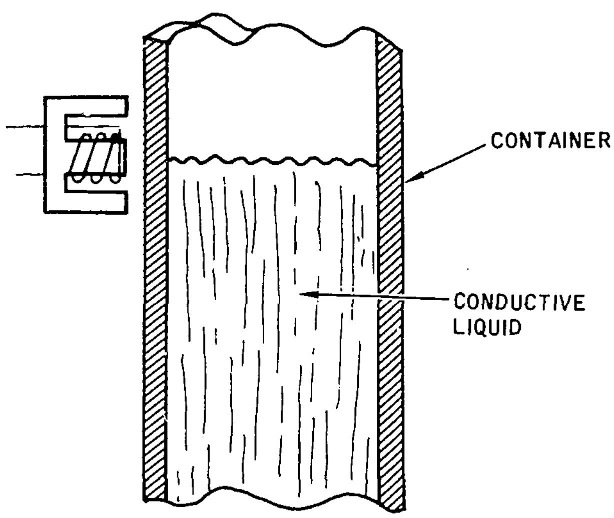


Figure 6-12. Determination of Fluid Level

607 CONDUCTIVE GAS

It is known that gases can be conductive under certain conditions of pressure, temperature, and ion concentration. Since eddy currents can be induced under these conditions, some form of measurement can be made.

1. CONCENTRATION

Measuring the ability of a gas to carry electrons can be used to determine pressure, temperature, or concentration of the gas. This would serve as a means to control or monitor an ionized gas stream. (Figure 6-13.)

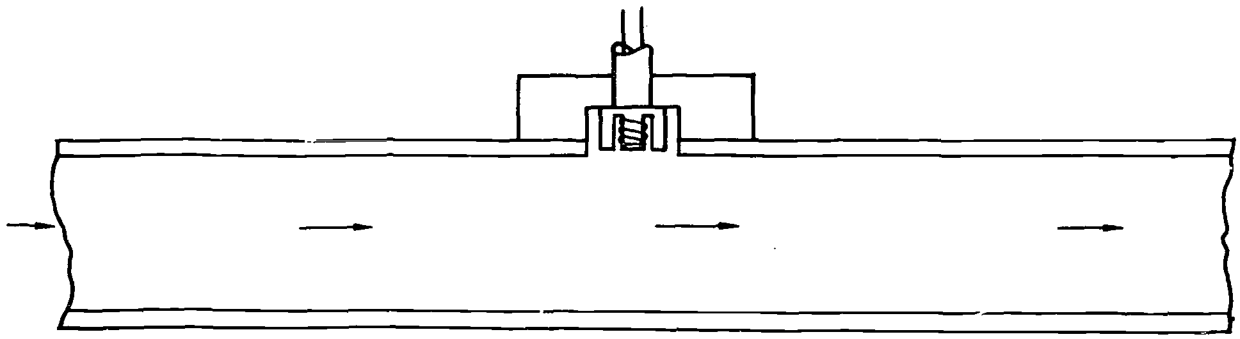


Figure 6-13. Conductivity Measurement of Ionized Gas Stream

2. BOUNDARY LOCATION

Since even a very weak conductibility of a gas to electrons can be detected by eddy current means, it is possible to detect lift-off changes. This lift-off measurement can define the boundary of such a conductive gas, e.g., envelope control of plasma. (Figure 6-14.)

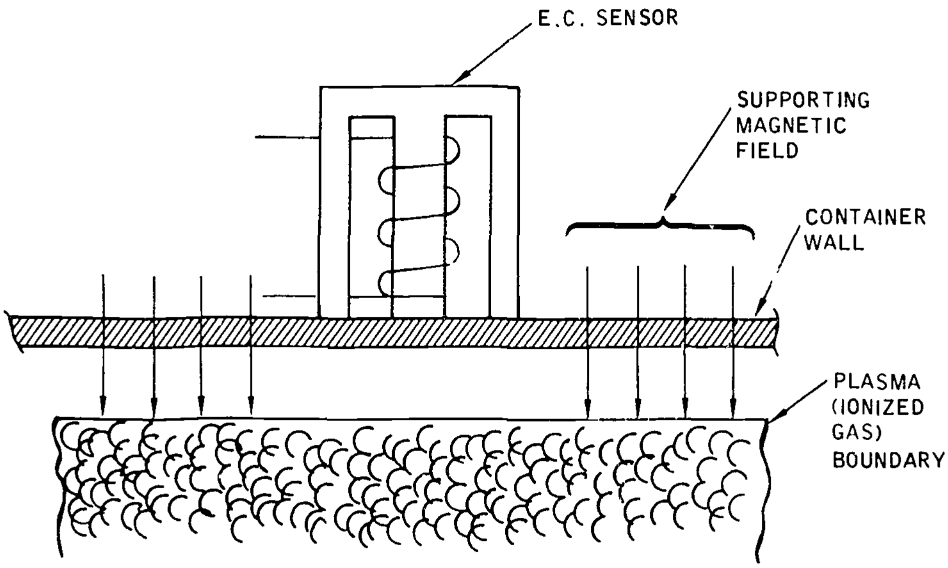


Figure 6-14. Boundary Determination in Ionized Gas

CHAPTER 7: COMPARISON AND SELECTION OF NDT PROCESSES
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CHAPTER 7: COMPARISON AND SELECTION OF NDT PROCESSES

700 GENERAL

The purpose of this chapter is to summarize the characteristics of various types of discontinuities, and to list the NDT methods which may be employed to detect each type of discontinuity.

The relationship between the various NDT methods and their capabilities and limitations when applied to the detection of a specific discontinuity will be shown. Such variables as type of discontinuity (inherent, process, or service), manufacturing processes (heat treating, machining, or plating), and limitations (metallurgical, structural, or processing) all will help determine the sequence of testing and the ultimate selection of one test method over another.

701 METHOD IDENTIFICATION

Figures 7-1 through 7-5 illustrate five NDT methods. Each illustration shows the three elements involved in all five tests, the different methods in each test category, and tasks that may be accomplished with a specific method.

702 NDT DISCONTINUITY SELECTION

The discontinuities that will be reviewed in paragraphs 706 through 732 are only a part of the many hundreds that are associated with the various products of the aerospace industry. During the selection of discontinuities for inclusion in this section, only a few of those discontinuities which would not be radically changed under different conditions of design, configuration, standards, and environment were chosen.

703 DISCONTINUITY CATEGORIES

Each of the specific discontinuities are divided into three general categories: inherent, processing, and service. Each of these categories is further classified as to whether the discontinuity is associated with ferrous or nonferrous materials, the specific material configuration, and the manufacturing processes if applicable.

1. INHERENT DISCONTINUITIES

Inherent discontinuities are those discontinuities that are related to the solidification of the molten metal. There are two types.

a. Wrought. Inherent wrought discontinuities cover those discontinuities which are related to the melting and original solidification of the metal or ingot.

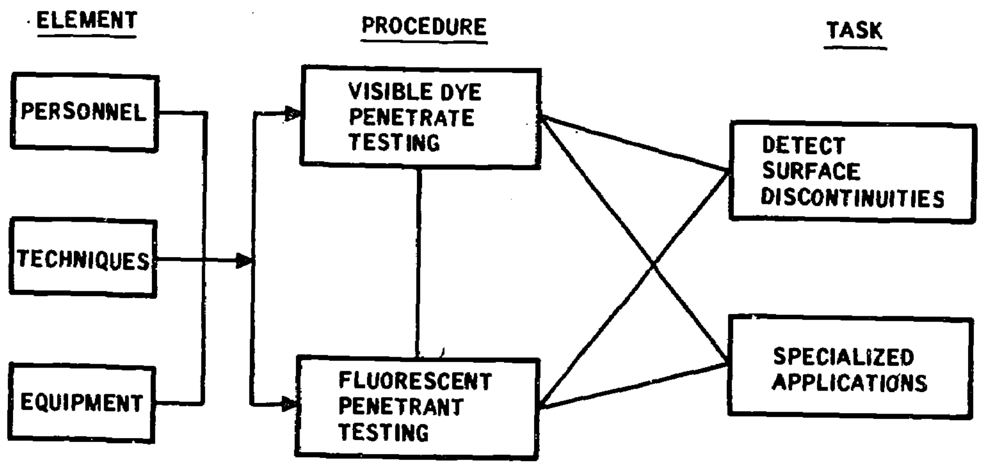


Figure 7-1. Liquid Penetrant Test

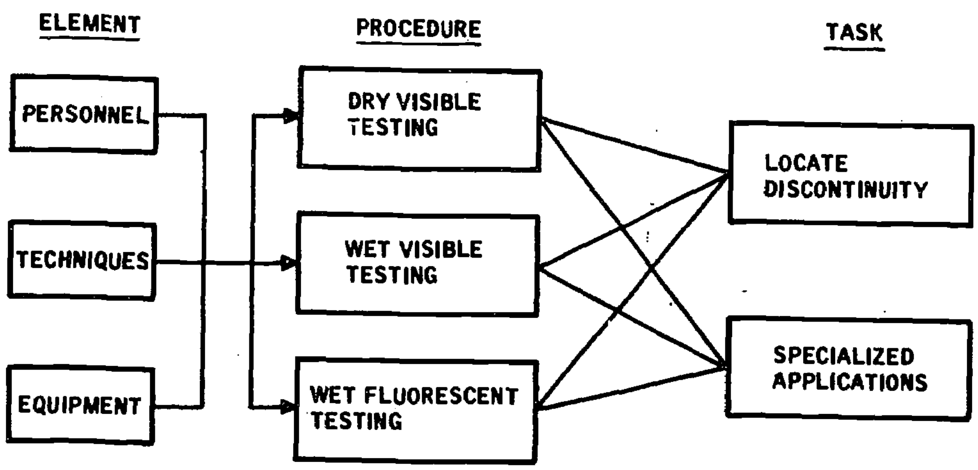


Figure 7-2. Magnetic Particle Test

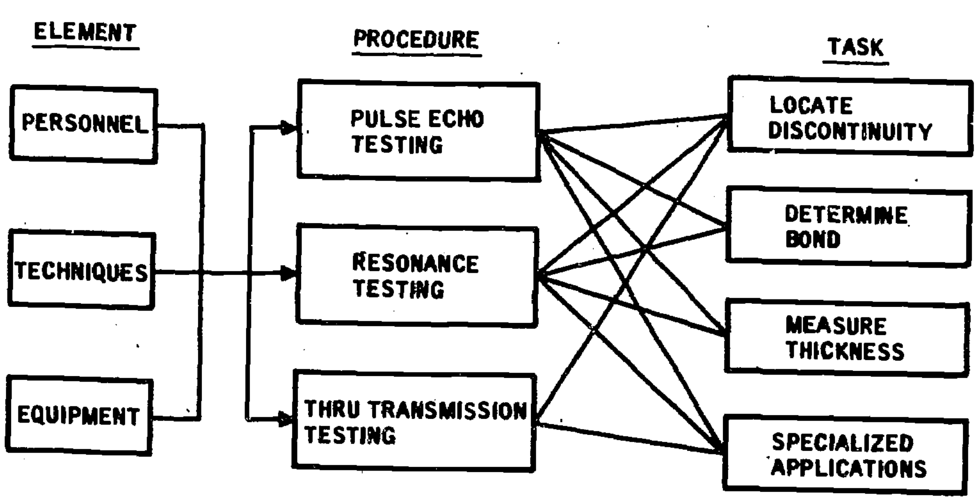


Figure 7-3. Ultrasonic Test

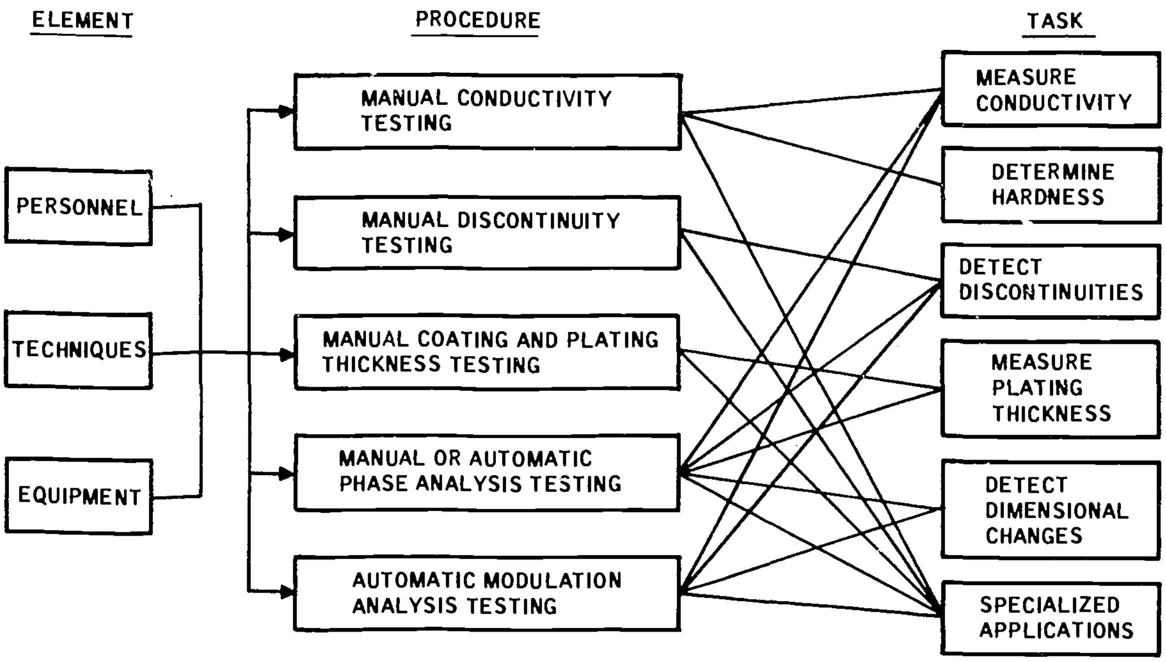


Figure 7-4. Eddy Current Test

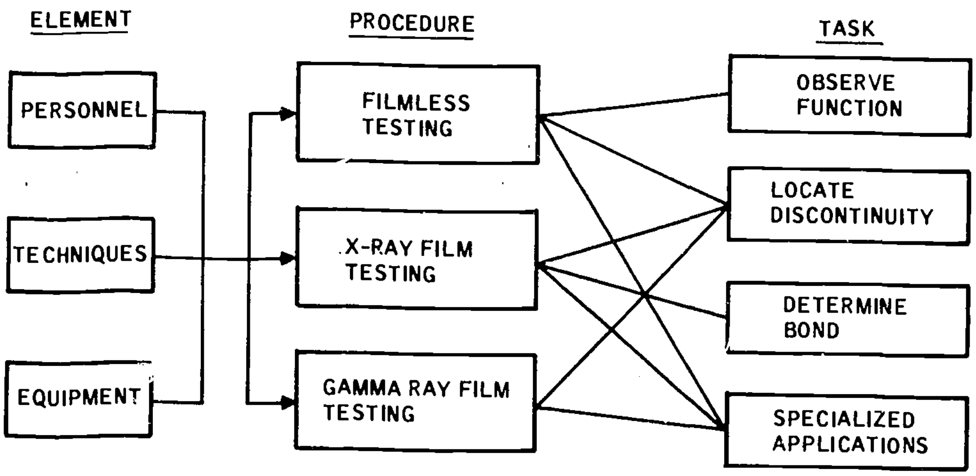


Figure 7-5. Radiographic Test

b. Cast. Inherent cast discontinuities are those discontinuities which are related to the melting, casting, and solidification of the cast article. It includes those discontinuities that would be inherent to manufacturing variables such as inadequate feeding, gating, excessively high pouring temperature, entrapped gases, handling, and stacking.

2. PROCESSING DISCONTINUITIES

Processing discontinuities are those discontinuities that are related to the various manufacturing processes such as machining, forming, extruding, rolling, welding, heat treating, and plating.

3. SERVICE DISCONTINUITIES

Service discontinuities cover those discontinuities that are related to the various service conditions such as stress corrosion, fatigue, and errosion.

704 DISCONTINUITY CHARACTERISTICS AND METALLURGICAL ANALYSIS

Discontinuity characteristics encompasses an analysis of the specific discontinuity and reference actual photos that illustrate examples of the discontinuity. The discussion will cover:

a. Origin and location of discontinuity (surface, near surface, or internal).

b. Orientation (parallel or normal to the grain).

c. Shape (flat, irregularly shaped, or spiral).

d. Photo (micrograph and/or typical overall view of the discontinuity).

e. Metallurgical analysis (how the discontinuity is produced and at what stage of manufacture).

705 NDT METHODS APPLICATION AND LIMITATIONS

1. GENERAL

The technological accomplishments in the field of nondestructive testing have brought the level of test reliability and reproducibility to a point where the design engineer may now selectively zone the specific article. This zoning is based upon the structural application of the end product and takes into consideration the environment as well as the loading characteristics of the article. Such an evaluation in no way reduces the end reliability of the product, but it does reduce needless rejection of material that otherwise would have been acceptable.

Just as the structural application within the article varies, the allowable discontinuity size will vary depending on the method of manufacture and configuration. For example, a die forging that has large masses of material and extremely thin web sections would not require the same level of acceptance for the whole forging. The forging can be zoned for rigid control where the structural applications are higher, and zoned for less rigid control where the structural requirements permit larger discontinuities.

The nondestructive testing specialist must also select the method which will satisfy the design objective of the specific article and not assume that all NDT methods can produce the same reliability for the same type of discontinuity.

2. SELECTION OF THE NDT METHOD

In selecting the NDT method for the evaluation of a specific discontinuity it should be kept in mind that NDT methods may supplement each other and that several NDT methods may be capable of performing the same task. The selection of one method over another is based upon variables such as:

a. Type and origin of discontinuity

b. Material manufacturing processes

c. Accessibility of article

d. Level of acceptability desired

e. Equipment available

f. Cost

To satisfactorily develop knowledge of the above variables, a planned analysis of the task must be made for each article requiring NDT testing.

The NDT methods listed for each discontinuity in paragraphs 706 through 732 are in order of preference for that particular discontinuity. However, when reviewing that portion of the chapter it should be kept in mind that the rapidly developing NDT field and new techniques may alter the order of test preference.

3. LIMITATIONS

The limitations applicable to the various NDT methods will vary with the applicable standard, the material, and the service environment. Limitations not only affect the NDT test, but in many cases the structural reliability of the test article is affected. For these reasons, limitations that are listed for one discontinuity may also be applicable to other discontinuities under slightly different conditions of material or environment. In addition, the many combinations of environment, location, material, and test capability do not permit mentioning all limitations that may be associated with a specific discontinuity. The intent of this chapter is fulfilled if you are made aware of the many factors that influence the selection of a valid NDT test.

706 BURST

1. CATEGORY. Processing

2. MATERIAL. Ferrous and Nonferrous Wrought Material

3. DISCONTINUITY CHARACTERISTICS

Surface or internal. Straight or irregular cavities varying in size with large interfaces or very tight. Usually parallel with the grain. Found in wrought material which required forging, rolling, or extruding. (See Figure 7-6.)

4. METALLURGICAL ANALYSIS

   a. Forging bursts are surface or internal ruptures which are attributed to processing at an incorrect temperature, or excessive working or metal movement during the forging, rolling, or extruding operation.

   b. A burst does not have a spongy appearance and, therefore, is distinguishable from a pipe, even if it should occur at the center.

   c. Bursts are often large and very seldom healed during subsequent working.

5. NDT METHODS APPLICATION AND LIMITATIONS

   a. ULTRASONIC TESTING METHOD

      (1) Normally used for the detection of internal bursts.

      (2) Bursts are definite breaks in the material and they resemble a crack, producing a very sharp reflection on the scope.

      (3) Ultrasonic testing is capable of detecting varying degrees of burst which could not be detected by other NDT methods.

      (4) Nicks, gouges, raised areas, tool tears, foreign material, gas bubbles on the article may produce adverse ultrasonic test results.

   b. EDDY CURRENT TESTING METHOD. Not normally used. Testing is restricted to wire, rod, and other articles under 0.250 inch diameter.

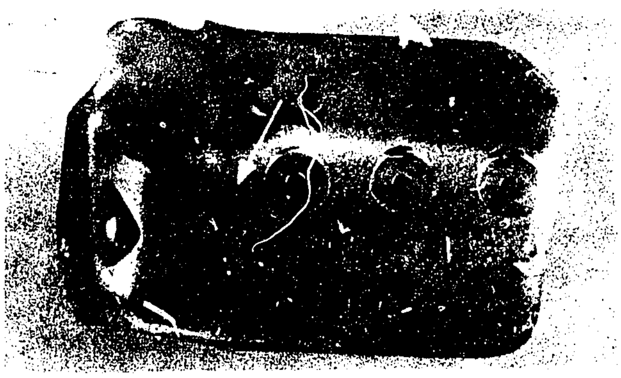
   c. MAGNETIC PARTICLE TESTING METHOD

      (1) Usually used on wrought ferrous material that has surface or exposed internal burst.

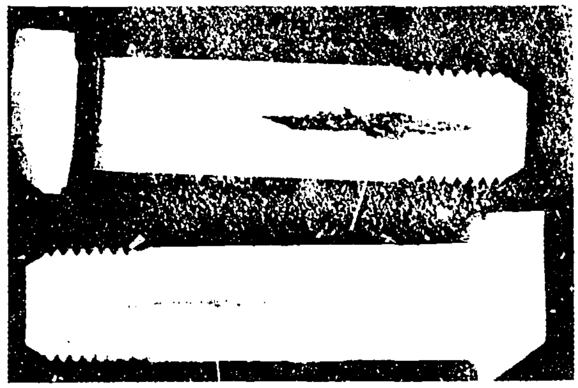
      (2) Results are limited to surface and near surface evaluation.

   d. LIQUID PENETRANT TESTING METHOD. Not normally used. When fluorescent penetrant is to be applied to an article previously dye penetrant tested, all traces of dye penetrant should first be removed by prolonged cleaning in applicable solvent.

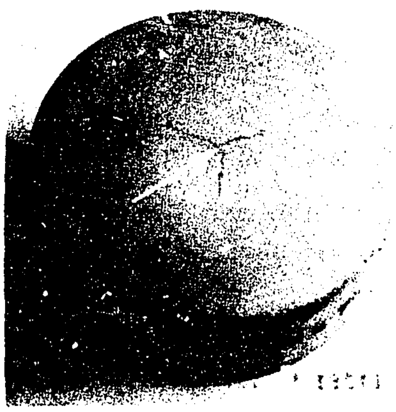
e. RADIOGRAPHIC TESTING METHOD. Not normally used. Such variables as the direction of the burst, close interfaces, wrought material, discontinuity size, and material thickness restrict the capability of radiography.



A FORGING EXTERNAL BURST



B BOLT INTERNAL BURST



C ROLLED BAR INTERNAL BURST

D FORGED BAR INTERNAL BURST

Figure 7-6. Burst Discontinuities

707 COLD SHUTS

1. CATEGORY. Inherent

2. MATERIAL. Ferrous and Nonferrous Cast Material

3. DISCONTINUITY CHARACTERISTICS

Surface and subsurface. Generally smooth indentations on the cast surface resembling a forging lap. (See Figure 7-7.)

4. METALLURGICAL ANALYSIS

Cold shuts are produced during casting molten metal. They may result from splashing, surging, interrupted pouring, or meeting of two streams of metal coming from different directions. Also, solidification of one surface before the other metal flows over it, the presence of interposing surface films on cold, sluggish metal, or any factor that will prevent a fusion where two surfaces meet will produce cold shuts. They are more prevalent in castings which are formed in a mold with several sprues or gates.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. LIQUID PENETRANT TESTING METHOD.

(1) Normally used to evaluate surface cold shuts in both ferrous and non-ferrous materials.

(2) Will appear as a smooth, regular, continuous, or intermittent indication, reasonably parallel to the cross section of the area in which it occurs.

(3) Liquid penetrant used for the testing of nickel base alloys (such as Inconel "X," Rene 41) should not exceed 0.5 percent sulfur.

(4) Certain castings may have surfaces which may be blind and from which removal of the excessive penetrants may be difficult.

(5) Geometric configuration (recesses, orifices, and flanges) may permit buildup of wet developer thereby masking any detection of a dis-continuity.

b. MAGNETIC PARTICLE TESTING METHOD

(1) Normally used for the screening of ferrous materials.

(2) The metallurgical nature of 431 corrosion-resistant steel is such that in some cases magnetic particle testing indications are obtained which do not result from a crack or other harmful discontinuities. These indications arise from a duplex structure within the material, wherein one portion exhibits strong magnetic retentivity and the other does not.

c. RADIOGRAPHIC TESTING METHOD

(1) Normally detectable by radiography while testing for other casting discontinuities.

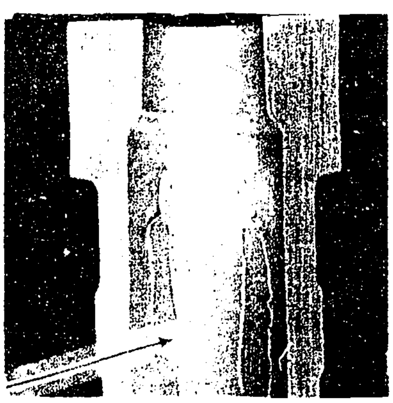
(2) Appear as a distinct dark line or band of variable length and width, and definite smooth outline.

(3) Casting configuration may have inaccessible areas which can only be detected by radiography.

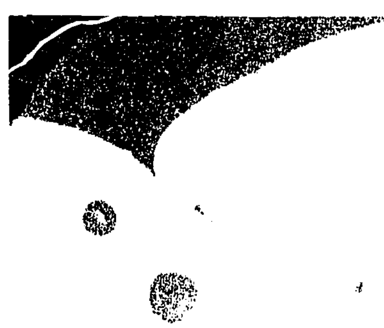
d. ULTRASONIC TESTING METHOD. Not recommended. Cast structure and article configuration do not as a general rule lend themselves to ultrasonic testing.

e. EDDY CURRENT TESTING METHOD. Not recommended. Article configuration and inherent material variables restrict the use of this method.

A SURFACE COLD SHUT



B INTERNAL COLD SHUT



C SURFACE COLD SHUT MICROGRAPH

Figure 7-7. Cold Shuts Discontinuity

708 FILLET CRACKS (BOLTS)

1. CATEGORY. Service

2. MATERIAL. Ferrous and Nonferrous Wrought Material

3. DISCONTINUITY CHARACTERISTICS

Surface. Located at the junction of the fillet with the shank of the bolt and progressing inward. (See Figure 7-8.)

4. METALLURGICAL ANALYSIS

Fillet cracks occur where a marked change in diameter occurs, such as between the head-to-shank junction where stress risers are created. During the application of this bolt in service repeated loading takes place, whereby the tensile load fluctuates in magnitude due to the operation of the mechanism. These tensile loads can cause fatigue failure, starting at the point where the stress risers are built in. Fatigue failure, which is surface phenomenon, starts at the surface and propagates inward.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. ULTRASONIC TESTING METHOD

(1) Used extensively for service associated discontinuities of this type.

(2) A wide selection of transducers and equipment enable on the spot evaluation for fillet crack.

(3) Being a definite break in the material, the scope pattern will be a very sharp reflection. (Actual propagation can be monitored by using ultrasonics.)

(4) Ultrasonic equipment has extreme sensitivity, and established standards should be used to give reproducible and reliable results.

b. LIQUID PENETRANT TESTING METHOD

(1) Normally used during in-service overhaul or troubleshooting.

(2) May be used for both ferrous and nonferrous bolts, although usually confined to the nonferrous.

(3) Will appear as a sharp clear indication.

(4) Structural damage may result from exposure of high strength steels to paint strippers, alkaline coating removers, deoxidizer solutions, etc.

(5) Entrapment under fasteners, in holes, under splices, and in similar areas may cause corrosion due to the penetrant's affinity for moisture.

c. MAGNETIC PARTICLE TESTING METHOD

(1) Normally used on ferrous bolts.

(2) Will appear as clear sharp indication with a heavy buildup.

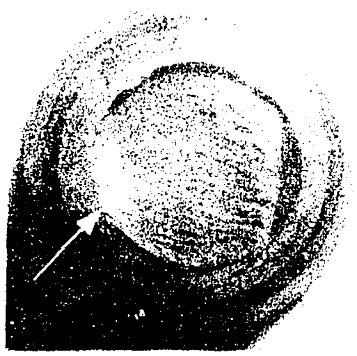
(3) Sharp fillet areas may produce non-relevant magnetic indications.

(4) 17.7 pH is only slightly magnetic in the annealed condition, but becomes strongly magnetic after heat treatment, when it may be magnetic particle tested.

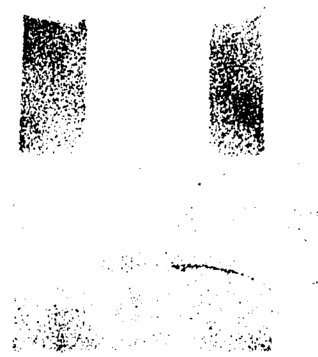
d. EDDY CURRENT TESTING METHOD. Not normally used for detection of fillet cracks. Other NDT methods are more compatible to the detection of this type of discontinuity.

e. RADIOGRAPHIC TESTING METHOD. Not normally used for detection of fillet cracks. Surface discontinuities of this type would be difficult to evaluate due to size of crack in relation to the thickness of material.

A FILLET FATIGUE FAILURE



B FRACTURE AREA OF (A) SHOWING TANGENCY POINT OF FAILURE



C CROSS-SECTIONAL AREA OF FATIGUE CRACK IN FILLET SHOWING TANGENCY POINT IN RADIUS

Figure 7-8. Fillet Crack Discontinuity

709 GRINDING CRACKS

1. CATEGORY. Processing

2. MATERIAL. Ferrous and Nonferrous

3. DISCONTINUITY CHARACTERISTICS

Surface. Very shallow and sharp at the root. Similar to heat treat cracks and usually, but not always, occur in groups. Grinding cracks are generally at right angles to the direction of grinding. They are found in highly heat treated articles, chrome plated, case hardened and ceramic materials that are subjected to grinding operations. (See Figure 7-9.)

4. METALLURGICAL ANALYSIS

Grinding of hardened surfaces frequently introduces cracks. These thermal cracks are caused by local overheating of the surface being ground. The overheating is usually caused by lack of or poor coolant, a dull or improperly ground wheel, too rapid feed, or too heavy cut.

5. NDT METHODS APPLICATION AND LIMITATIONS

   a. LIQUID PENETRANT TESTING METHOD

      (1) Normally used on both ferrous and nonferrous materials for the detection of grinding cracks.

      (2) Liquid penetrant indication will appear as irregular, checked, or shattered pattern of fine lines.

      (3) Cracks are the most difficult discontinuity to indicate and require the longest penetration time.

      (4) Articles that have been degreased may still have solvent entrapped in the discontinuity and should be allowed sufficient time for evaporation prior to the application of the penetrant.

   b. MAGNETIC PARTICLE TESTING METHOD

      (1) Restricted to ferrous materials.

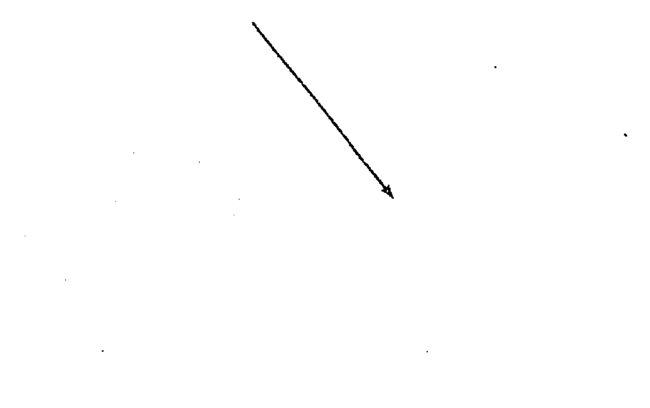
      (2) Grinding cracks are generally at right angles to grinding direction, although in extreme cases a complete network of cracks may appear, in which case they may be parallel to the magnetic field.

      (3) Magnetic sensitivity decreases as the size of grinding crack decreases and as its depth below the surface increases.

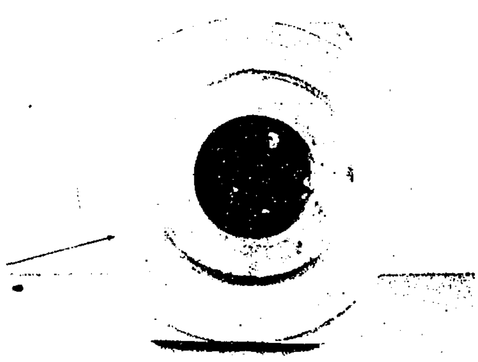
c. EDDY CURRENT TESTING METHOD. Not normally used for detection of grinding cracks. Eddy current equipment has the capability and can be developed for a specific nonferrous application.

d. ULTRASONIC TESTING METHOD. Not normally used for detection of grinding cracks. Other forms or NDT are more economical, faster, and better adapted to this type of discontinuity than ultrasonics.

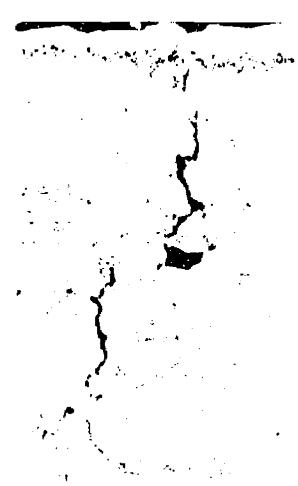
e. RADIOGRAPHIC TESTING METHOD. Not recommended for detection of grinding cracks. Grinding cracks are too tight and small. Other NDT methods are more suitable for detection of grinding cracks.



A TYPICAL CHECKED GRINDING CRACK PATTERN



B GRINDING CRACK PATTERN NORMAL TO GRINDING



C MICROGRAPH OF GRINDING CRACK

Figure 7-9. Grinding Crack Discontinuity

710 CONVOLUTION CRACKS

1. CATEGORY. Processing

2. MATERIAL. Nonferrous

3. DISCONTINUITY CHARACTERISTICS

Surface. Range in size from micro fractures to open fissures. Situated on the periphery of the convolutions and extend longitudinally in direction of rolling. (See Figure 7-10.)

4. METALLURGICAL ANALYSIS

The rough 'orange peel' effect of convolution cracks is the result of either a forming operation which stretches the material or from chemical attack such as pickling treatment. The roughened surface contains small pits which form stress risers. Subsequent service application (vibration and flexing) may introduce stresses that act on these pits and form fatigue cracks as shown in the accompanying photograph.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. RADIOGRAPHIC TESTING METHOD

(1) Used extensively for this type of failure.

(2) Configuration of article and location of discontinuity limits detection almost exclusively to radiography.

(3) Orientation of convolutions to X-ray source is very critical since those discontinuities which are not normal to X-ray may not register on the film due to the lack of difference in density.

(4) Liquid penetrant and magnetic particle testing may supplement but not replace radiographic and ultrasonic testing.

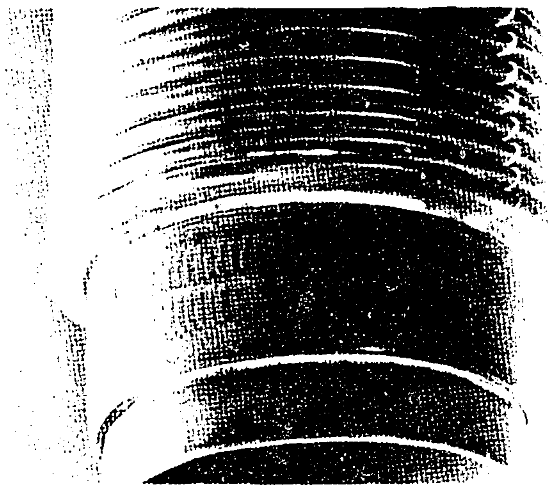
(5) The type of marking material (e.g., grease pencil on titanium) used to identify the area of discontinuities may affect the structure of the article.

b. ULTRASONIC TESTING METHOD. Not normally used for the detection of convolution cracks. Configuration of the article (double-walled convolutions) and internal micro fractures are all factors which restrict the use of ultrasonics.

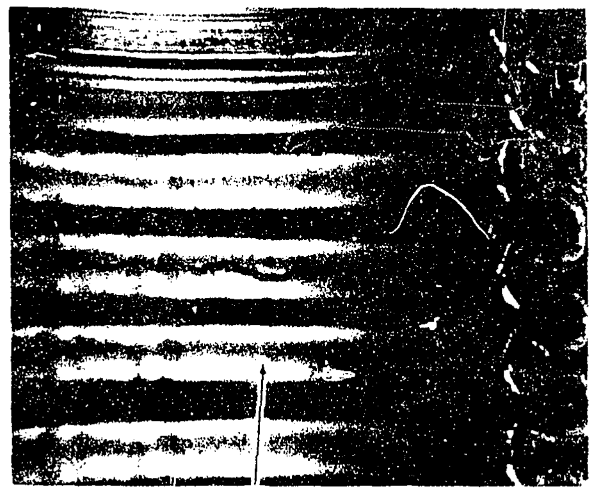
c. EDDY CURRENT TESTING METHOD. Not normally used for the detection of convolution cracks. As in the case of ultrasonic testing, the configuration does not lend itself to this method of testing.

d. LIQUID PENETRANT TESTING METHOD. Not recommended for the detection of convolution cracks. Although the discontinuities are surface, they are internal and are superimposed over an exterior shell which creates a serious problem of entrapment.

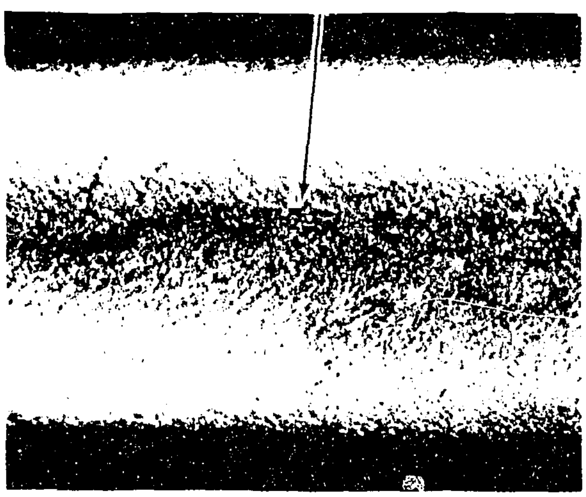
e. MAGNETIC TESTING METHOD. Not applicable. Material is nonferrous.



A TYPICAL CONVOLUTION DUCTING



B CROSS-SECTION OF CRACKED CONVOLUTION



C HIGHER MAGNIFICATION OF CRACK SHOWING ORANGE PEEL

D MICROGRAPH OF CONVOLUTION WITH PARTIAL CRACKING ON SIDES

Figure 7-10. Convolution Cracks Discontinuity

711 HEAT-AFFECTED ZONE CRACKING

1. CATEGORY. Processing (Weldments)

2. MATERIAL. Ferrous and Nonferrous

3. DISCONTINUITY CHARACTERISTICS

Surface. Often quite deep and very tight. Usually parallel with the weld in the heat-affect zone of the weldment. (See Figure 7-11.)

4. METALLURGICAL ANALYSIS

Hot cracking of heat-affected zones of weldments increases in severity with increasing carbon content. Steels that contain more than 0.30% carbon are prone to this type of failure and require preheating prior to welding.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. MAGNETIC PARTICLE TESTING METHOD

(1) Normally used for ferrous weldments.

(2) Prod burns are very detrimental, especially on highly heat treated articles. May contribute to structural failure of article.

(3) Demagnetization of highly heat treated articles can be very difficult due to metallurgical structure.

b. LIQUID PENETRANT TESTING METHOD

(1) Normally used for nonferrous weldments.

(2) Material that has had its surface obliterated, blurred, or blended due to manufacturing processes should not be penetrant tested until the smeared surface has been removed.

(3) Liquid penetrant testing after the application of certain types of chemical film coatings may be invalid due to the covering or filling of the discontinuities.

c. RADIOGRAPHIC TESTING METHOD. Not normally used for the detection of heat-affected zone cracking. Discontinuity orientation and surface origin make other NDT methods more suitable.

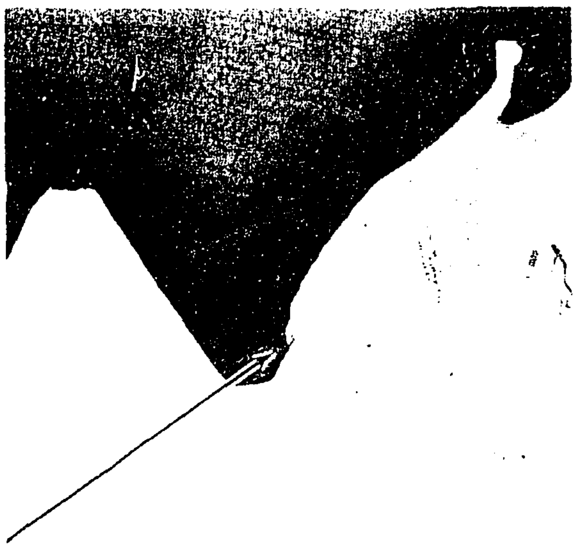
d. ULTRASONIC TESTING METHOD

(1) Used where specialized applications have been developed.

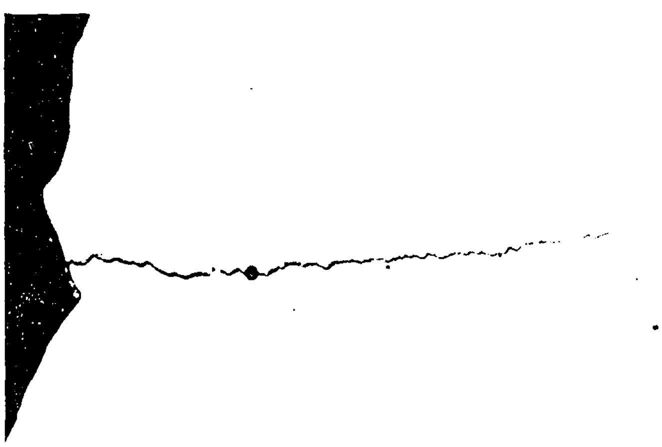
(2) Rigid standards and procedures are required to develop valid tests.

(3) The configuration of the surface roughness (i.e., sharp versus rounded root radii and the slope condition) are major factors in deflecting the sound beam.

e. EDDY CURRENT TESTING METHOD. Not normally used for the detection of heat-affected zone cracking. Eddy current equipment has capability of detecting nonferrous surface discontinuities; however, it is not as universally used as magnetic particle or liquid penetrant.



A MICROGRAPH OF WELD AND HEAT-AFFECTED ZONE SHOWING CRACK NOTE COLD LAP WHICH MASKS THE ENTRANCE TO THE CRACK .



B MICROGRAPH OF CRACK SHOWN IN (A)

Figure 7-11. Heat-Affected Zone Cracking Discontinuity

712 HEAT TREAT CRACKS

1. CATEGORY. Processing

2. MATERIAL. Ferrous and Nonferrous Wrought and Cast Material

3. DISCONTINUITY CHARACTERISTICS

Surface. Usually deep and forked. Seldom follow a definite pattern and can be in any direction on the part. Originate in areas with rapid change of material thickness, sharp machining marks, fillets, nicks, and discontinuities which have been exposed to the surface of the material. (See Figure 7-12.)

4. METALLURGICAL ANALYSIS

During the heating and cooling process localized stresses may be set up by unequal heating or cooling, restricted movement of the article, or unequal cross-sectional thickness. These stresses may exceed the tensile strength of the material causing it to rupture. Where built-in stress risers occur (keyways or grooves) additional cracks may develop.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. MAGNETIC PARTICLE TESTING METHOD

(1) For ferrous materials, heat treat cracks are normally detected by magnetic particles testing.

(2) The magnetic particles indications will normally be straight, forked, or curved indications.

(3) Likely points of origin are areas that would develop stress risers, such as keyways, fillets, or areas with rapid changes in material thickness.

(4) Metallurgical structure of age hardenable and heat treatable stainless steels (17.4, 17.7, and 431) may produce irrelevant indications.

b. LIQUID PENETRANT TESTING METHOD

(1) For nonferrous materials liquid penetrant testing is the recommended method.

(2) Likely points of origin would be the same as those listed above for magnetic particle testing.

(3) Materials or articles that will eventually be used in LOX systems must be tested with compatible penetrants.

c. EDDY CURRENT TESTING METHOD

(1) Normally not used.

(2) Magnetic particles and liquid penetrant are more direct and economical.

d. ULTRASONIC TESTING METHOD. Not normally used for detection of heat treat cracks. If used the scope pattern will show a definite indication of a discontinuity. Recommended wave mode would be surface.

e. RADIOGRAPHIC TESTING METHOD. Not normally used for detection of heat treat cracks. Surface discontinuities are more easily detected by other NDT methods designed for surface application.

A FILLET AND MATERIAL THICKNESS CRACKS (TOP CENTER)
RELIEF RADIUS CRACKING (LOWER LEFT)

B HEAT TREAT CRACK DUE TO SHARP MACHINING MARKS

Figure 7-12. Heat Treat Cracks Discontinuity

713 SURFACE SHRINK CRACKS

1. CATEGORY. Processing (Welding)

2. MATERIAL. Ferrous and Nonferrous

3. DISCONTINUITY CHARACTERISTICS

Surface. Situated on the face of the weld, fusion zone, and base metal. Range in size from very small, tight, and shallow, to open and deep. Cracks may run parallel or transverse the direction of welding. (See Figure 7-13.)

4. METALLURGICAL ANALYSIS

Surface shrink cracks are generally the result of improper heat application, either in heating or welding of the article. Heating or cooling in a localized area may set up stresses that exceed the tensile strength of the material causing the material to crack. Restriction of the movement (contraction or expansion) of the material during heating, cooling, or welding may also set up excessive stresses.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. LIQUID PENETRANT TESTING METHOD

(1) Surface shrink cracks are normally detected by liquid penetrant.

(2) Liquid penetrant equipment is easily portable and can be used during in-process control for both ferrous and nonferrous weldments.

(3) Assemblies which are joined by bolting, riveting, intermittent welding, or press fittings will retain the penetrant, which will seep out after developing and mask the adjoining surfaces.

(4) When articles are dried in a hot air dryer or by similar means, excessive drying temperature should be avoided to prevent evaporation of the penetrant.

b. MAGNETIC PARTICLE TESTING METHOD

(1) Ferrous weldments are normally tested by magnetic particle method.

(2) Surface discontinuities that are parallel to the magnetic field will not produce indications since they do not interrupt or distort the magnetic field.

(3) Areas of grease fittings, bearing races, or other similar items that might be damaged or clogged by the suspension solution or magnetic solids should be masked before testing.

c. EDDY CURRENT TESTING METHOD

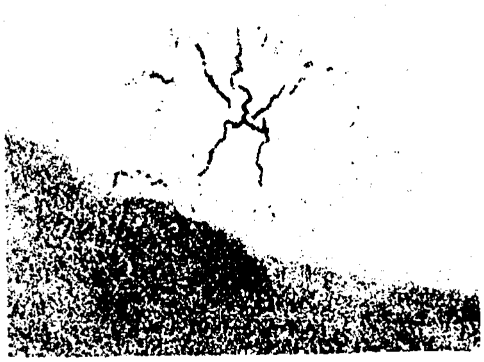
(1) Normally confined to nonferrous welded pipe and tubing.

(2) Probe or encircling coil could be used where article configuration permits.

d. RADIOGRAPHIC TESTING METHOD. Not normally used for the detection of surface discontinuities. During the radiographic testing of weldments for other types of discontinuities, surface indications may be detected.

e. ULTRASONIC TESTING METHOD. Not normally used for detection of surface shrink cracks. Other forms of NDT (liquid penetrant and magnetic particle) give better results, are more economical, and are faster.

A TRANSVERSE CRACKS IN HEAT-AFFECTED ZONE



B TYPICAL STAR-SHAPED CRATER CRACK

C SHRINKAGE CRACK AT WELD TERMINAL

Figure 7-13. Surface Shrink Crack Discontinuity

714 THREAD CRACKS

1. CATEGORY. Service

2. MATERIAL. Ferrous and Nonferrous Wrought Material

3. DISCONTINUITY CHARACTERISTICS

Surface. Cracks are transverse to the grain (transgranular) starting at the root of the thread. (See Figure 7-14.)

4. METALLURGICAL ANALYSIS

Fatigue failures of this type are not uncommon. High cyclic stresses resulting from vibration and/or flexing act on the stress risers created by the thread roots and produce cracks. Fatigue cracks may start as fine submicroscopic discontinuities and/or cracks and propagate in the direction of applied stresses.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. LIQUID PENETRANT TESTING METHOD

(1) Fluorescent penetrant is recommended over non-fluorescent.

(2) Low surface tension solvents such as gasoline and kerosene are not recommended cleaners.

(3) When applying liquid penetrant to components within an assembly or structure, the adjacent areas should be effectively masked to prevent overspraying.

b. MAGNETIC PARTICLE TESTING METHOD

(1) Normally used on ferrous materials.

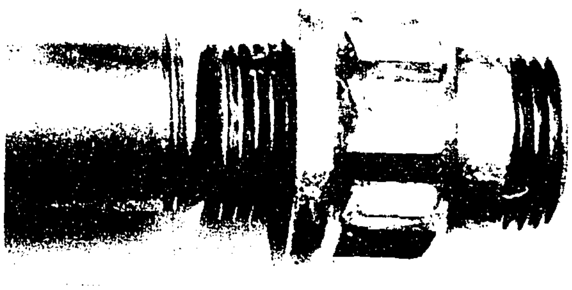
(2) Irrelevent magnetic indications may result from the thread configuration.

(3) Cleaning titanium and 440C stainless in halogeneated hydrocarbons may result in structural damage to the material.

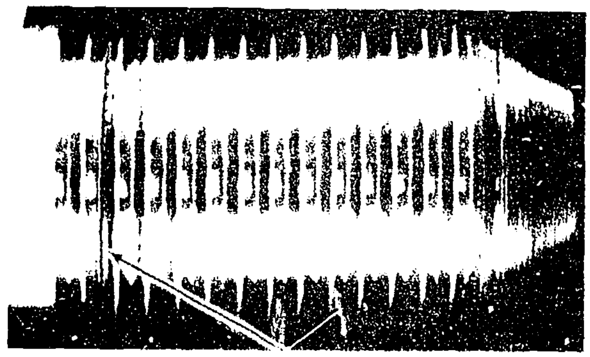
c. EDDY CURRENT TESTING METHOD. Not normally used for detecting thread cracks. The article configuration would require specialized equipment if adaptable.

d. ULTRASONIC TESTING METHOD. Not recommended for detecting thread cracks. Thread configuration does not lend itself to ultrasonic testing.

e. RADIOGRAPHIC TESTING METHOD. Not recommended for detecting thread cracks. Surface discontinuities are best screened by NDT method designed for the specific condition. Fatigue cracks of this type are very tight and surface connected, their detection by radiography would be extremely difficult.



A COMPLETE THREAD ROOT FAILURE



B TYPICAL THREAD ROOT FAILURE

C MICROGRAPH OF (A) SHOWING CRACK AT BASE OF ROOT

D MICROGRAPH OF (B) SHOWING TRANSGRANULAR CRACK AT THREAD ROOT

Figure 7-14. Thread Crack Discontinuity

715 TUBING CRACKS (INCONEL "X")

1. CATEGORY. Inherent

2. MATERIAL. Nonferrous

3. DISCONTINUITY CHARACTERISTICS

Tubing cracks formed on the inner surface (I.D.), parallel to direction of grain flow. (See Figure 7-15.)

4. METALLURGICAL ANALYSIS

Tubing I.D. cracks may be attributed to one or a combination of the following:

a. Improper cold reduction of the tube during fabrication.

b. Foreign material may have been embedded on the inner surface of the tubes causing embrittlement and cracking when the cold worked material was heated during the annealing operation.

c. Insufficient heating rate to the annealing temperature with possible cracking occurring in the 1200-1400° F range.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. EDDY CURRENT TESTING METHOD

(1) Normally used for detection of this type of discontinuity.

(2) The diameter (1 inch) and wall thickness (0.156 inch) are well within equipment capability.

(3) Testing of ferro-magnetic material may be difficult.

b. ULTRASONIC TESTING METHOD

(1) Normally used on heavy gauge tubing.

(2) A wide variety of equipment and transducers are available for screening tubing for internal discontinuities of this type.

(3) Ultrasonic transducers have varying temperature limitations.

(4) Certain ultrasonic contact couplants may have high sulfur content which will have an adverse effect on high nickel alloys.

c. RADIOGRAPHIC TESTING METHOD

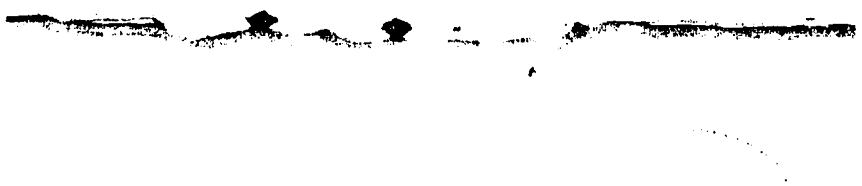
(1) Not normally used for detecting tubing cracks.

(2) Discontinuity orientation and thickness of material govern the radiographic sensitivity.

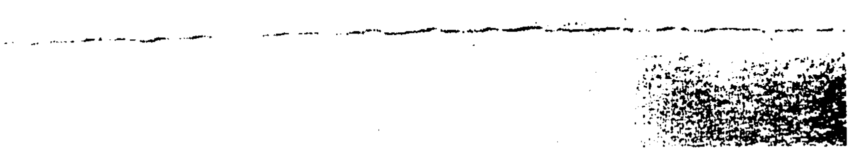
(3) Other forms of NDT (eddy current and ultrasonic) are more economical, faster, and reliable.

d. LIQUID PENETRANT TESTING METHOD. Not recommended for detecting tubing cracks. Internal discontinuity would be difficult to process and interpret.

e. MAGNETIC PARTICLES TESTING METHOD. Not applicable. Material is nonferrous under normal conditions.



A TYPICAL CRACK ON INSIDE OF TUBING SHOWING COLD LAP



B ANOTHER PORTION OF SAME CRACK SHOWING CLEAN FRACTURE

C MICROGRAPH OF (B)

Figure 7-15. Tubing Crack Discontinuity

716 HYDROGEN FLAKE

1. CATEGORY. Processing

2. MATERIAL. Ferrous

3. DISCONTINUITY CHARACTERISTICS

Internal fissures in a fractured surface, flakes appear as bright silvery areas. On an etched surface they appear as short discontinuities. Sometimes known as chrome checks and hairline cracks when revealed by machining, flakes are extremely thin and generally aligned parallel with the grain. They are usually found in heavy steel forgings, billets, and bars. (See Figure 7-16.)

4. METALLURGICAL ANALYSIS

Flakes are internal fissures attributed to stresses produced by localized transformation and decreased solubility of hydrogen during cooling after hot working. Usually found only in heavy alloy steel forgings.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. ULTRASONIC TESTING METHOD

(1) Used extensively for the detection of hydrogen flake.

(2) Material in the wrought condition can be screened successfully using either the immersion or the contact method. The surface condition will determine the method most suited.

(3) On the A-scan presentation, hydrogen flake will appear as hash on the screen or as loss of back reflection.

(4) All foreign materials (loose scale, dirt, oil, grease) should be removed prior to any testing. Surface irregularities such as nicks, gouges, tool marks, and scarfing may cause loss of back reflection.

b. MAGNETIC PARTICLE TESTING METHOD

(1) Normally used on finished machined articles.

(2) Flakes appear as short discontinuities and resemble chrome checks or hairline cracks.

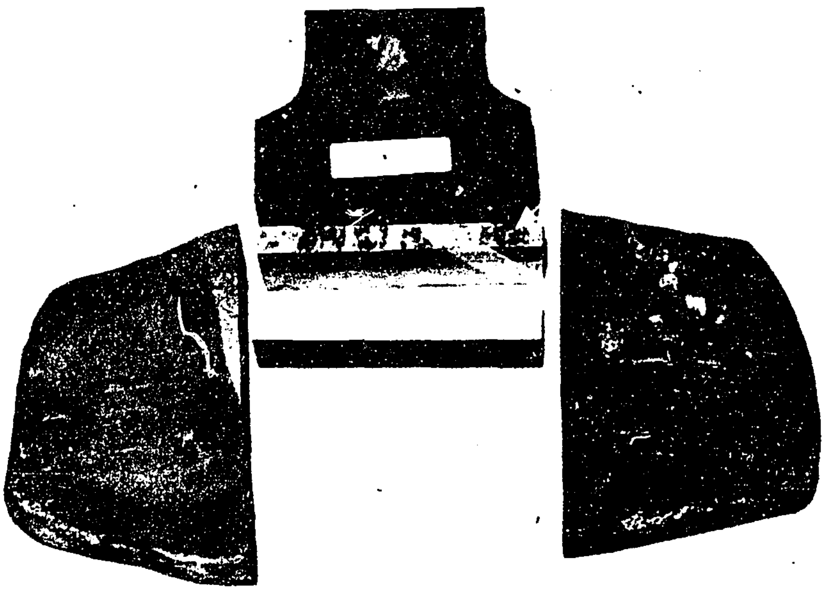
(3) Machined surfaces with deep tool marks may obliterate the detection of the flake.

(4) Where the general direction of a discontinuity is questionable, it may be necessary to magnetize in two or more directions.

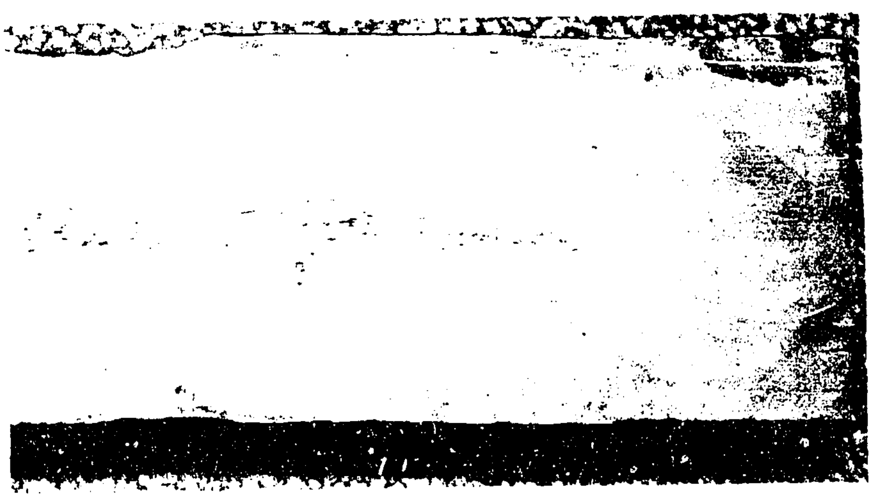
c. LIQUID PENETRANT TESTING METHOD. Not normally used for detecting flakes. Discontinuities are very small and tight and would be difficult to detect by liquid penetrant.

d. EDDY CURRENT TESTING METHOD. Not recommended for detecting flakes. The metallurgical structure of ferrous materials limits their adaptability to the use of eddy current.

e. RADIOGRAPHIC TESTING METHOD. Not recommended for detecting flakes. The size of the discontinuity, its location and orientation with respect to the material surface restricts the application of radiography.



A 4340 CMS HAND FORGING REJECTED FOR HYDROGEN FLAKE



B CROSS-SECTION OF (A) SHOWING FLAKE CONDITION IN CENTER OF MATERIAL

Figure 7-16. Hydrogen Flake Discontinuity

717 HYDROGEN EMBRITTLEMENT

1. CATEGORY. Processing and Service

2. MATERIAL. Ferrous

3. DISCONTINUITY CHARACTERISTICS

Surface. Small, nondimensional (interface) with no orientation or direction. Found in highly heat treated material that was subjected to pickling and/or plating or in material exposed to free hydrogen. (See Figure 7-17.)

4. METALLURGICAL ANALYSIS

Operations such as pickling and cleaning prior to electroplating or electroplating generate hydrogen at the surface of the material. This hydrogen penetrates the surface of the material creating immediate or delayed embrittlement and cracking.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. MAGNETIC PARTICLES TESTING METHOD

(1) Magnetic indications appear as a fractured pattern.

(2) Hydrogen embrittlement cracks are randomly orientated and may follow the magnetic field.

(3) Magnetic particle testing should be accomplished before and after plating.

(4) Care should be taken to produce no confusing or irrelevant indications or cause damage to the article by overheating.

(5) 301 corrosion resistant steel is non-magnetic in the annealed condition, but becomes magnetic with cold working.

b. LIQUID PENETRANT TESTING METHOD

(1) Not normally used for detecting hydrogen embrittlement.

(2) Discontinuities on the surface are extremely tight, small, and difficult to detect. Subsequent plating deposit may mask the discontinuity.

c. ULTRASONIC TESTING METHOD

(1) Not normally used for detecting hydrogen embrittlement.

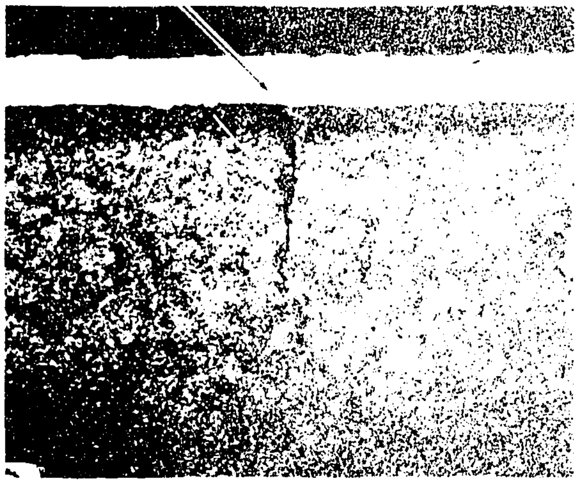
(2) Article configurations and size do not, in general, lend themselves to this method of testing.

(3) Equipment has capability of detecting hydrogen embrittlement. Recommend surface wave technique.

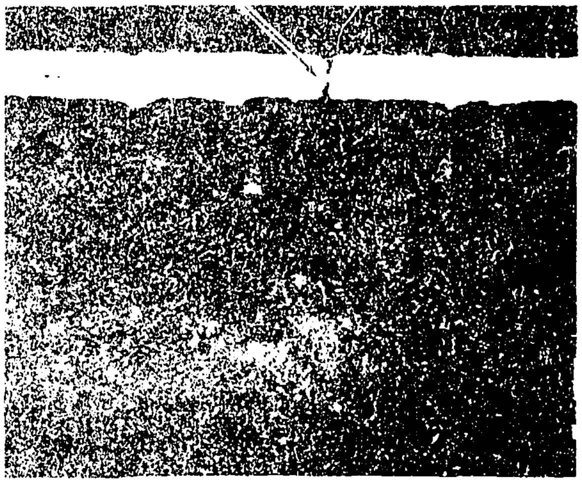
d. EDDY CURRENT TESTING METHOD. Not recommended for detecting hydrogen embrittlement. Many variables inherent in the specific material may produce conflicting patterns.

e. RADIOGRAPHIC TESTING METHOD. Not recommended for detecting hydrogen embrittlement. The sensitivity required to detect hydrogen embrittlement is in most cases in excess of radiographic capabilities.

A DETAILED CRACK PATTERN OF HYDROGEN EMBRITTLEMENT



B HYDROGEN EMBRITTLEMENT UNDER CHROME PLATE



C HYDROGEN EMBRITTLEMENT PROPAGATED THROUGH CHROME PLATE

Figure 7-17. Hydrogen Embrittlement Discontinuity

718 INCLUSIONS

1. CATEGORY. Processing (Weldments)

2. MATERIAL. Ferrous and Nonferrous Welded Material

3. DISCONTINUITY CHARACTERISTICS

Surface and subsurface. Inclusions may be any shape. They may be metallic or non-metallic and may appear singly or be linearly distributed or scattered throughout the weldment. (See Figure 7-18.)

4. METALLURGICAL ANALYSIS

Metallic inclusions are generally particles of metals of different density as compared to the weld or base metal. Non-metallic inclusions are oxides, sulphides, slag or other non-metallic foreign material entrapped in the weld or between the weld metal and the base metal.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. RADIOGRAPHIC TESTING METHOD

(1) This NDT method is universally used.

(2) Metallic inclusions appear on the radiograph as sharply defined, round, erratically shaped, or elongated white spots and may be isolated or in small linear or scattered groups.

(3) Non-metallic inclusions will appear on the radiograph as shadows of round globules or elongated or irregularly shaped contours occurring singly, linearly, or scattered throughout the weldment. They will generally appear in the fusion zone or at the root of the weld. Less absorbent material is indicated by a greater film density and more absorbent materials by a lighter film density.

(4) Foreign material such as loose scales, splatter, or flux may invalidate test results.

b. EDDY CURRENT TESTING METHOD

(1) Normally confined to thin wall welded tubing.

(2) Established standards may be required if valid results are to be obtained.

c. MAGNETIC PARTICLE TESTING METHOD

(1) Normally not used for detecting inclusions in weldments.

(2) Confined to machined weldments where the discontinuities are surface or near surface.

(3) The indications would appear jagged, irregularly shaped, individually or clustered, and would not be too pronounced.

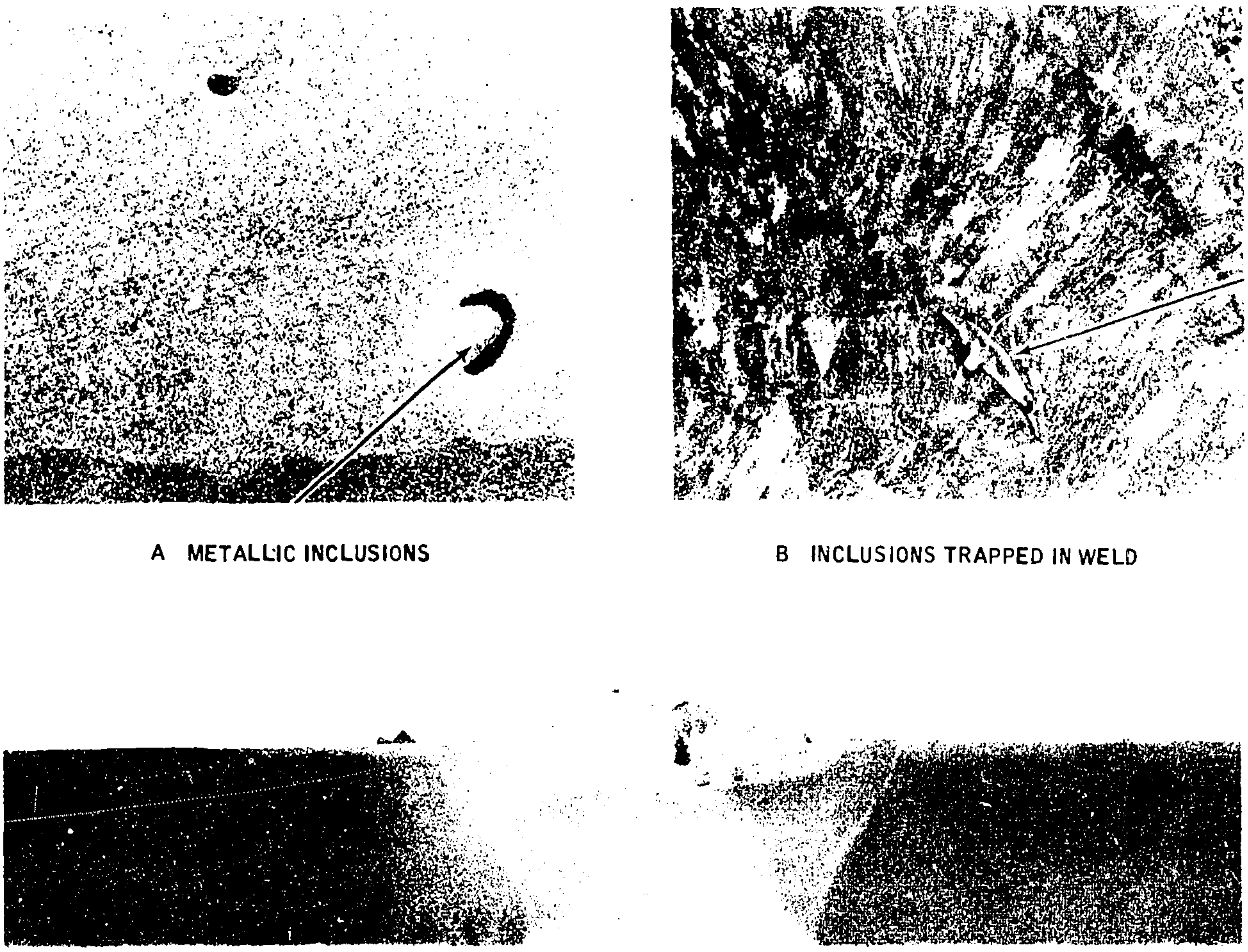
(4) Discontinuities may go undetected when improper contact exists between the magnetic particles and the surface of the article.

d. ULTRASONIC TESTING METHOD

(1) Not normally used for detecting inclusions.

(2) Specific applications of design or of article configuration may require ultrasonic testing.

e. LIQUID PENETRANT TESTING METHOD. Not applicable. Inclusions are normally not open fissures.



A METALLIC INCLUSIONS

B INCLUSIONS TRAPPED IN WELD

C CROSS-SECTION OF WELD SHOWING INTERNAL INCLUSIONS

Figure 7-18. Weldment Inclusion Discontinuity

719 INCLUSIONS

1. CATEGORY. Processing

2. MATERIAL. Ferrous and Nonferrous Wrought Material

3. DISCONTINUITY CHARACTERISTICS

Subsurface (original bar) or surface (after machining). There are two types: one is non-metallic with long straight lines parallel to flow lines and quite tightly adherent. Often short and likely to occur in groups. The other type is non-plastic, appearing as a comparatively large mass and not parallel to flow lines. Found in forged, extruded, and rolled material. (See Figure 7-19.)

4. METALLURGICAL ANALYSIS

Non-metallic inclusions (stringers) are caused by the existence of slag or oxides in the billet or ingot. Non-plastic inclusions are caused by particles remaining in the solid state during billet melting.

5. NDT METHODS APPLICATIONS AND LIMITATIONS

a. ULTRASONIC TESTING METHOD

(1) Normally used to evaluate inclusions in wrought material.

(2) Inclusions will appear as definite interfaces within the metal. Small clustered condition or conditions on different planes causing a loss in back reflection. Numerous small scattered conditions cause excessive "noise".

(3) Inclusion orientation in relationship to ultrasonic beam is critical.

(4) The direction of the ultrasonic beam should be perpendicular to the direction of the grain flow whenver possible.

b. EDDY CURRENT TESTING METHOD

(1) Normally used for thin wall tubing and small diameter rods.

(2) Testing of ferro-magnetic materials can be difficult.

c. MAGNETIC PARTICLE TESTING METHOD

(1) Normally used on machined surface.

(2) Inclusions will appear as a straight intermittent or as a continuous indication. They may be individual or clustered.

(3) The magnetic technique should be such that a surface or near surface inclusion can be satisfactorily detected when its axis is in any direction.

(4) A knowledge of the grain flow of the material is critical since inclusions will be parallel to that direction.

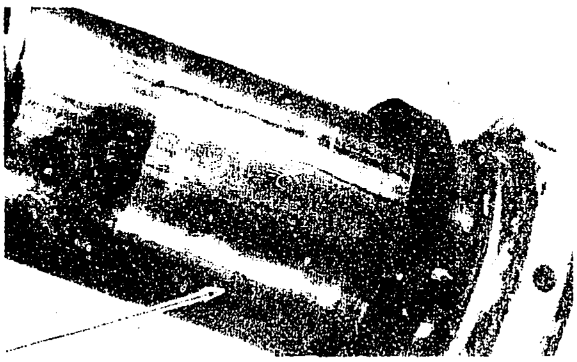
(5) Certain types of steels are more prone to inclusions than other.

d. LIQUID PENETRANT TESTING METHOD

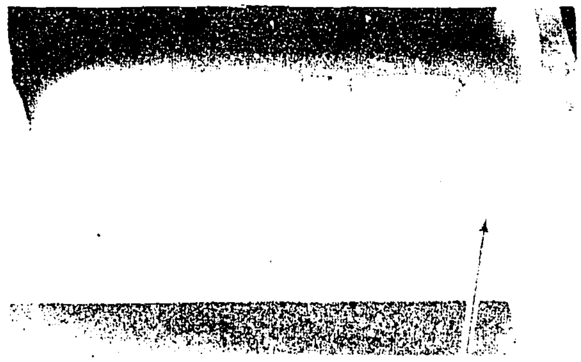
(1) Not normally used for detecting inclusions in wrought material.

(2) Inclusions are generally not openings in the material surface.

e. RADIOGRAPHIC TESTING METHOD. Not recommended. NDT methods designed for surface testing are more suitable for detecting surface inclusions.

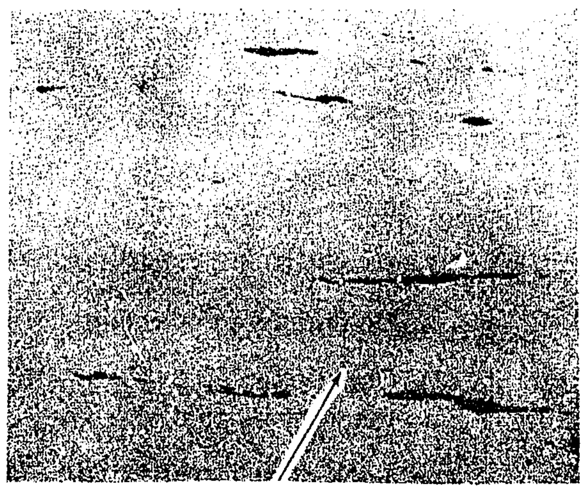


A TYPICAL INCLUSION PATTERN ON MACHINED SURFACES



B STEEL FORGING SHOWING NUMEROUS INCLUSIONS

C MICROGRAPH OF TYPICAL INCLUSION



D LONGITUDINAL CROSS-SECTION SHOWING ORIENTATION OF INCLUSIONS

Figure 7-19. Wrought Inclusion Discontinuity

720 LACK OF PENETRATION

1. CATEGORY. Processing

2. MATERIAL. Ferrous and Nonferrous Weldments

3. DISCONTINUITY CHARACTERISTICS

Internal or external. Generally irregular and filamentary occuring at the root and running parallel with the weld. (See Figure 7-20.)

4. METALLURGICAL ANALYSIS

Caused by root face of joint not reaching fusion temperature before weld metal was deposited. Also caused by fast welding rate, too large a welding rod, or too cold a bead.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. RADIOGRAPHIC TESTING METHOD

(1) Used extensively on a wide variety of welded articles to determine the lack of penetration.

(2) Lack of penetration will appear on the radiograph as an elongated dark area of varying length and width. It may be continuous or intermittent and may appear in the center of the weld at the junction of multipass bends.

(3) Lack of penetration orientation in relationship to the radiographic source is critical.

(4) Sensitivity levels govern the capability to detect small or tight discontinuities.

b. ULTRASONIC TESTING METHOD

(1) Commonly used for specific applications.

(2) Complex weld configurations, or thin wall weldments do not lend themselves to ultrasonic testing.

(3) Lack of penetration will appear on the scope as a definite break or discontinuity resembling a crack and will give a very sharp reflection.

(4) Repeatability of ultrasonic test results is difficult unless equipment is standardized.

c. EDDY CURRENT TESTING METHOD

(1) Normally used to determine lack of penetration in nonferrous welded pipe and tubing.

(2) Eddy current can be used where other nonferrous articles can meet the configuration requirement of the equipment.

d. MAGNETIC PARTICLE TESTING METHOD

(1) Normally used where backside of weld is visible.

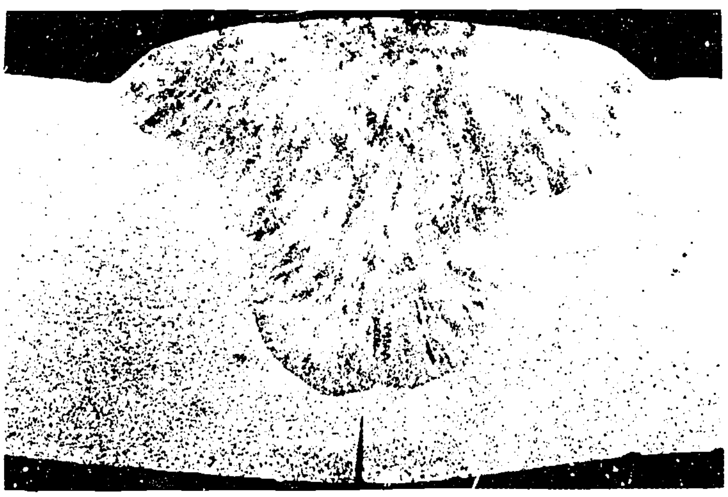
(2) Lack of penetration appears as an irregular indication of varying width.

e. LIQUID PENETRANT TESTING METHOD

(1) Normally used where backside of weld is visible.

(2) Lack of penetration appears as an irregular indication of varying width.

(3) Residue left by the penetrant and the developer could contaminate any re-welding operation.



A INADEQUATE ROOT PENETRATION

B INADEQUATE ROOT PENETRATION OF BUTT WELDED TUBE

C INADEQUATE FILLET WELD PENETRATION KNOWN AS BRIDGING

Figure 7-20. Lack of Penetration Discontinuity

721 LAMINATIONS

1. CATEGORY. Inherent

2. MATERIAL. Ferrous and Nonferrous Wrought Material

3. DISCONTINUITY CHARACTERISTICS

Surface and internal. Flat, extremely thin, generally aligned parallel to the work surface of the material. May contain a thin film of oxide between the surfaces. Found in forged, extruded, and rolled material. (See Figure 7-21.)

4. METALLURGICAL ANALYSIS

Laminations are separations or weaknesses generally aligned parallel to the work surface of the material. They may be the result of pipe, blister, seam, inclusions, or segregations elongated and made directional by working. Laminations are flattened impurities that are extremely thin.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. ULTRASONIC TESTING METHOD

(1) For heavier gauge material the geometry and orientation of lamination (normal to the beam) makes their detection limited to ultrasonic.

(2) Numerous wave modes may be used depending upon the material thickness or method selected for testing. Automatic and manual contact or immersion methods are adaptable.

(3) Lamination will appear as a definite interface with a loss of back reflection.

(4) Through transmission and reflection techniques are applicable for very thin sections.

b. MAGNETIC PARTICLE TESTING METHOD

(1) Articles fabricated from ferrous materials are normally tested for lamination by magnetic particle.

(2) Magnetic indication will appear as a straight, intermittent indication.

(3) Magnetic particle testing is not capable of determining the over-all size or depth of the lamination.

c. LIQUID PENETRANT TESTING METHOD

(1) Normally used on nonferrous materials.

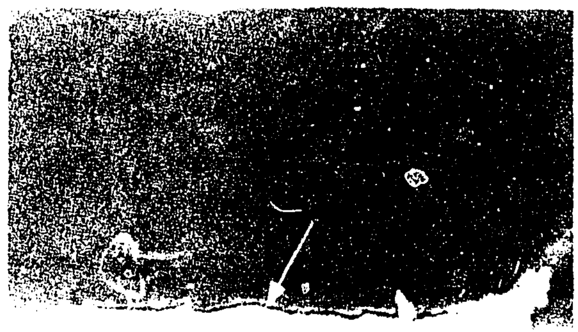
(2) Machining, honing, lapping, or blasting may smear surface of material and thereby close or mask surface lamination.

(3) Acid and alkalines seriously limit the effectiveness of liquid penetrant testing. Thorough cleaning of the surface is essential.

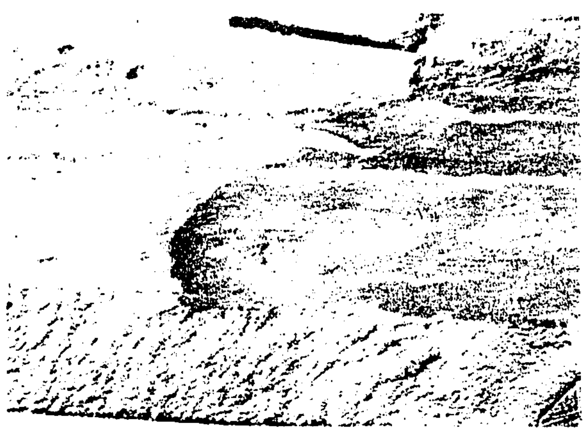
d. EDDY CURRENT TESTING METHOD. Not normally used to detect laminations. If used, the method must be confined to thin sheet stock.

e. RADIOGRAPHIC TESTING METHOD. Not recommended for detecting laminations Laminations have very small thickness changes in the direction of the X-ray beam, thereby making radiographic detection almost impossible.

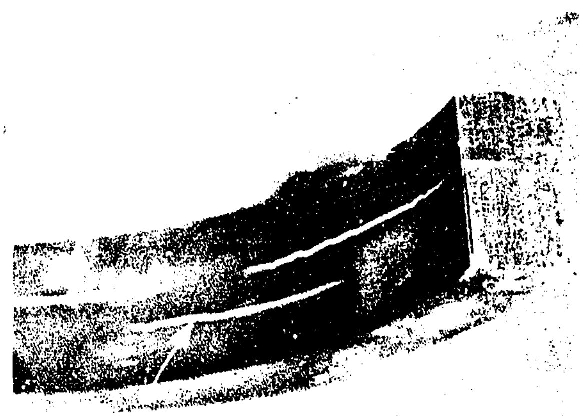
A LAMINATION IN 0.250 IN. PLATE



B LAMINATION IN 0.040 TITANIUM SHEET



C LAMINATION IN PLATE SHOWING SURFACE ORIENTATION



D LAMINATION IN 1 IN. BAR SHOWING SURFACE ORIENTATION

Figure 7-21. - Lamination Discontinuity

722 LAPS AND SEAMS

1. CATEGORY. Processing

2. MATERIAL. Ferrous and Nonferrous Rolled Threads

3. DISCONTINUITY CHARACTERISTICS

Surface. Wavy lines, often quite deep and sometime very tight, appearing as hairline cracks. Found in rolled threads in the minor, pitch, and major diameter of the thread, and in direction of rolling. (See Figure 7-22.)

4. METALLURGICAL ANALYSIS

During the rolling operation, faulty or oversized dies or an overfill of material may cause material to be folded over and flattened into the surface of the thread but not fused.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. LIQUID PENETRANT TESTING METHOD

(1) Compatibility with both ferrous and nonferrous materials makes fluorescent liquid penetrant the first choice.

(2) Liquid penetrant indications will be circumferential, slightly curved, intermittent or continuous indications. Laps and seams may occur individually or in clusters.

(3) Foreign material may not only interfere with the penetration of the penetrant into the discontinuity but may cause an accumulation of penetrant in a nondefective area.

(4) Surface of threads may be smeared due to rolling operation, thereby sealing off laps and seams.

(5) Fluorescent and dye penetrants are not compatible. Dye penetrants tend to kill the fluorescent qualities in fluorescent penetrants.

b. MAGNETIC PARTICLE TESTING METHOD

(1) Magnetic particle indications would generally appear the same as liquid penetrant.

(2) Irrelevent magnetic indications may result from the thread configuration.

(3) Questionable magnetic particles indications can be verified by liquid penetrant testing.

c. EDDY CURRENT TESTING METHOD. Not normally used for detecting laps and seams. Article configuration is the restricting factor.

d. ULTRASONIC TESTING METHOD. Not recommended for detecting laps and seams. Thread configurations restrict ultrasonic capability.

e. RADIOGRAPHIC TESTING METHOD. Not recommended for detecting laps and seams. Size and orientation of discontinuities restricts the capability of radiographic testing.

A TYPICAL AREAS OF FAILURE LAPS AND SEAMS

B FAILURE OCCURRING AT ROOT OF THREAD

C AREAS WHERE LAPS AND SEAMS USUALLY OCCUR

Figure 7-22. Laps and Seams Discontinuity in Rolled Threads

723 LAPS AND SEAMS

1. CATEGORY. Processing

2. MATERIAL. Ferrous and Nonferrous Wrought Material

3. DISCONTINUITY CHARACTERISTICS

   a. Lap Surface. Wavy lines usually not very pronounced or tightly adherent since they usually enter the surface at a small angle. Laps may have surface openings smeared closed. Found in wrought forgings, plate, tubing, bar, and rod. (See Figure 7-23.)

   b. Seam Surface. Lengthy, often quite deep and sometimes very tight, usually parallel fissures with the grain and at times spiral when associated with rolled rod and tubing.

4. METALLURGICAL ANALYSIS

Seams originate from blowholes, cracks, splits, and tears introduced in earlier processing and elongated in the direction of rolling or forging. The distance between adjacent innerfaces of the discontinuity is very small.

Laps are similar to seams and may result from improper rolling, forging, or sizing operations. During the processing of the material, corners may be folded over or an overfill may exist during the sizing resulting in material being flattened into the surface but not fused. Laps may occur on any part of the article.

5. NDT METHODS APPLICATION AND LIMITATIONS

   a. MAGNETIC PARTICLE TESTING METHOD

      (1) Magnetic particle is recommended for ferrous material.

      (2) Surface and near-surface laps and seams may be detected by this method.

      (3) Laps and seams may appear as a straight, spiral, or slightly curved indication. They may be individual or clustered and continuous or intermittent.

      (4) Magnetic buildup of laps and seams is very small. Therefore, a magnetizing current greater than that used for the detection of a crack is necessary.

      (5) Correct magnetizing technique should be used when examining for forging laps since the discontinuity may lie in a plane nearly parallel to the surface.

b. LIQUID PENETRANT TESTING METHOD

(1) Liquid penetrant is recommended for nonferrous material.

(2) Laps and seams may be very tight and difficult to detect especially by liquid penetrant.

(3) Liquid penetrant testing of laps and seams can be improved slightly by heating the article before applying the penetrant.

c. ULTRASONIC TESTING METHOD

(1) Normally used to test wrought material prior to machining.

(2) Surface wave technique permits accurate evaluation of the depth, length, and size of laps and seams.

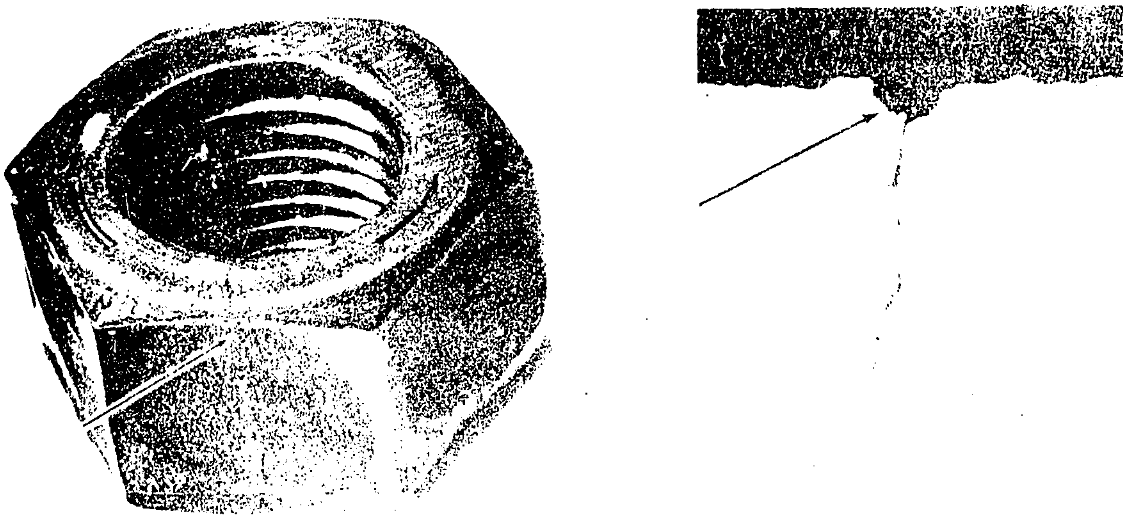
(3) Ultrasonic indication of laps and seams will appear as definite inner faces within the metal.

d. EDDY CURRENT TESTING METHOD

(1) Normally used for the evaluation of laps and seams in tubing and pipe.

(2) Other articles can be screened by eddy current where article configuration and size permit.

e. RADIOGRAPHIC TESTING METHOD. Not recommended for detecting laps and seams in wrought material. Although the ratio between the discontinuity size and the material thickness exceeds 2% of sensitivity in most cases, discontinuities have a very small thickness change in the direction of the X-ray beam, thereby making radiographic detection almost impossible.



A TYPICAL FORGING LAP

B MICROGRAPH OF A LAP

Figure 7-23. Laps and Seams Discontinuity in Wrought Material

724 MICRO-SHRINKAGE

1. CATEGORY. Processing

2. MATERIAL. Magnesium Casting

3. DISCONTINUITY CHARACTERISTICS

Internal. Small filamentary voids in the grain boundaries appear as concentrated porosity in cross section. (See Figure 7-24.)

4. METALLURGICAL ANALYSIS

Shrinkage occurs while the metal is in a plastic or semi-molten state. If sufficient molten metal cannot flow into different areas as it cools, the shrinkage will leave a void. The void is identified by its appearance and by the time in the plastic range it occurs. Micro-shrinkage is caused by the withdrawal of the low melting point constituent from the grain boundaries.

5. NDT METHODS APPLICATION AND LIMITATIONS

   a. RADIOGRAPHIC TESTING METHOD

      (1) Radiography is universally used to determine the acceptance level of micro-shrinkage.

      (2) Micro-shrinkage will appear on the radiograph as an elongated swirl resembling feathery streaks or as dark irregular patches, which are indicative of cavities in the grain boundaries.

   b. LIQUID PENETRANT TESTING METHOD

      (1) Normally used on finished machined surfaces.

      (2) Micro-shrinkage is not normally open to the surface. These conditions will, therefore, be detected in machined areas.

      (3) The appearance of the indication depends on the plane through which the condition has been cut. The appearance varies from a continuous hairline to a massive porous indication.

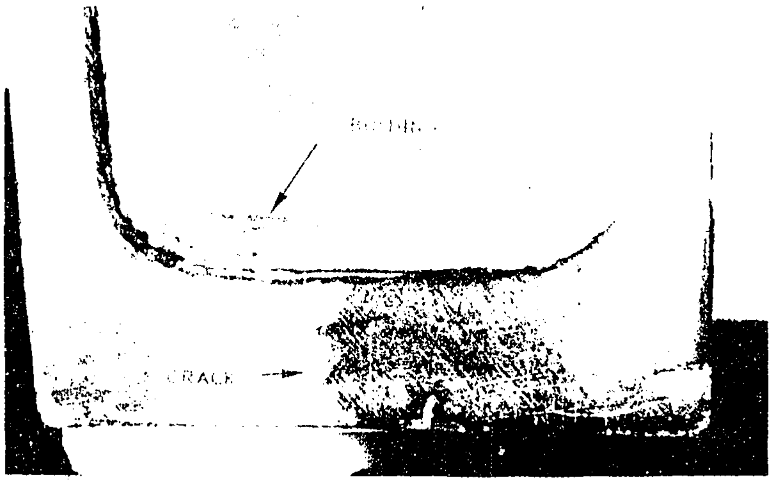
      (4) Penetrant may act as a contaminant by saturating the micro porous casting affecting their ability to accept a surface treatment.

      (5) Serious structural and a dimensional damage to the article can result from the improper use of acids or alkalies. They should never be used unless approval is obtained.

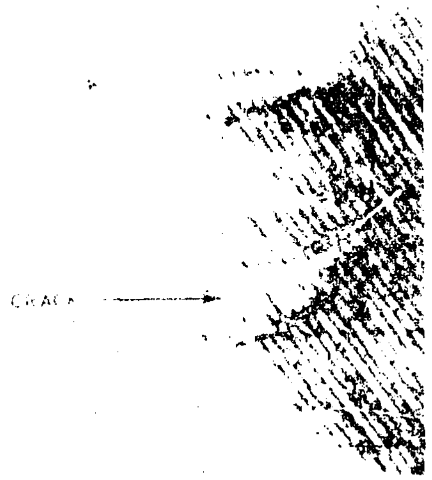
c. EDDY CURRENT TESTING METHOD. Not recommended for detecting micro-shrinkage. Article configuration and type of discontinuity do not lend themselves to eddy current.

d. ULTRASONIC TESTING METHOD. Not recommended for detecting micro-shrinkage. Cast structure and article configuration are restricting factors.

e. MAGNETIC PARTICLE TESTING METHOD. Not applicable. Material is nonferrous.



A CRACKED MAGNESIUM HOUSING



B CLOSE-UP VIEW OF (A)

C MICROGRAPH OF CRACKED AREA

Figure 7-24. Micro-Shrinkage Discontinuity

725 GAS POROSITY

1. CATEGORY. Processing

2. MATERIAL. Ferrous and Nonferrous Weldments

3. DISCONTINUITY CHARACTERISTICS

Surface or subsurface. Rounded or elongated, teardrop shaped with or without a sharp discontinuity at the point. Scattered uniformly throughout the weld or isolated in small groups. May also be concentrated at the root or toe. (See Figure 7-25.)

4. METALLURGICAL ANALYSIS

Porosity in welds is caused by gas entrapment in the molten metal, too much moisture on the base or filler metal, or improper cleaning or preheating.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. RADIOGRAPHY TESTING METHOD

(1) Radiography is the most universally used NDT method for the detection of gas porosity in weldments.

(2) The radiographic image of a 'round' porosity will appear as oval shaped spots with smooth edges, while 'elongated' porosity will appear as oval shaped spots with the major axis sometimes several times longer than the minor axis.

(3) Foreign material such as loose scale, flux, or splatter will affect validity of test results.

b. ULTRASONIC TESTING METHOD

(1) Ultrasonic testing equipment is highly sensitive, capable of detecting micro-separations. Established standards should be used if valid test results are to be obtained.

(2) Surface finish and grain size will affect the validity of the test results.

c. EDDY CURRENT TESTING METHOD

(1) Normally confined to thin wall welded pipe and tube.

(2) Penetration restricts testing to a depth of more than one-quarter inch.

d. LIQUID PENETRANT TESTING METHOD

(1) Normally confined to in-process control of ferrous and nonferrous weldments.

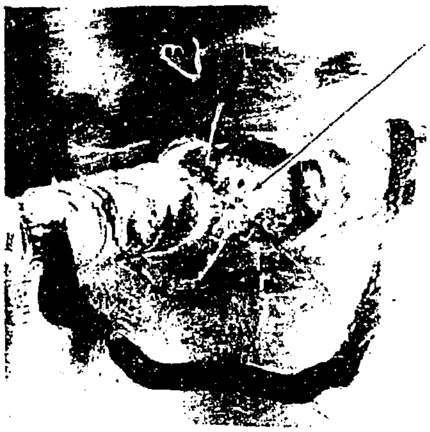
(2) Liquid penetrant testing, like magnetic particle, is restricted to surface evaluation.

(3) Extreme caution must be exercised to prevent any cleaning material, magnetic (iron oxide), and liquid penetrant materials from becoming entrapped and contaminating the rewelding operation.

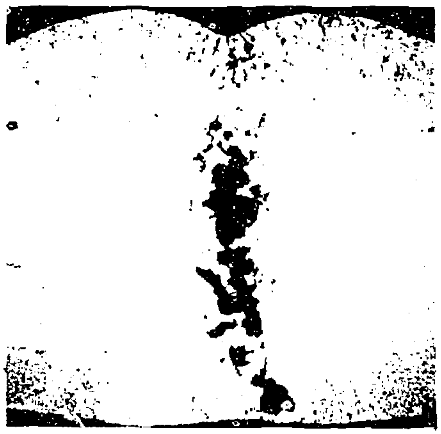
e. MAGNETIC PARTICLE TESTING METHOD

(1) Not normally used to detect gas porosity.

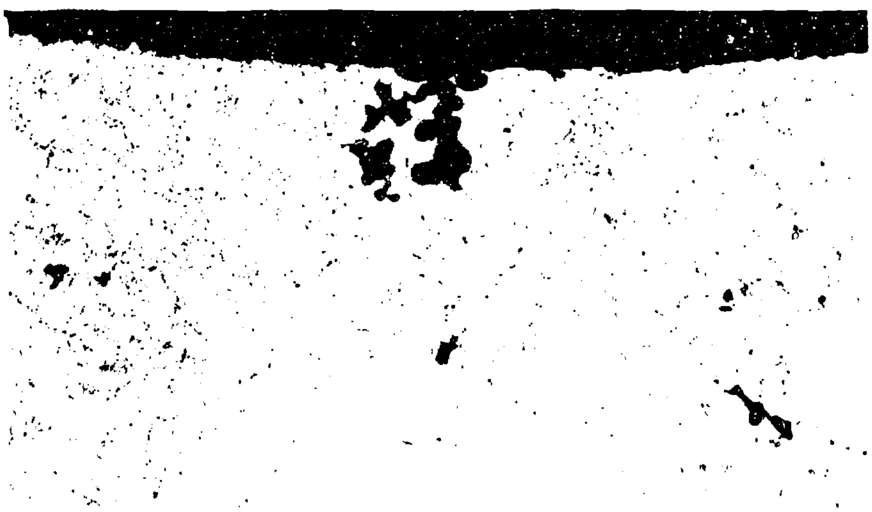
(2) Only surface porosity would be evident. Near surface porosity would not be clearly defined since it is neither strong or pronounced.



A TYPICAL SURFACE POROSITY



B CROSS-SECTION OF (A) SHOWING EXTENT OF POROSITY



C MICROGRAPH OF CROSS-SECTION SHOWING TYPICAL SHRINKAGE POROSITY

Figure 7-25. Gas Porosity Discontinuity

726 UNFUSED POROSITY

1. CATEGORY. Processing

2. MATERIAL. Aluminum

3. DISCONTINUITY CHARACTERISTICS

Internal. Wafer-thin fissures aligned parallel with the grain flow. Found in wrought aluminum which is rolled, forged, or extruded. (See Figure 7-26.)

4. METALLURGICAL ANALYSIS

Unfused porosity is attributed to porosity which is in the cast ingot. During the rolling, forging, or extruding operations it is flattened into wafer-thin shape. If the internal surface of these discontinuities is oxidized or is composed of a foreign material, they will not fuse during the subsequent processing, resulting in an extremely thin interface or void.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. ULTRASONIC TESTING METHOD

(1) Used extensively for the detection of unfused porosity.

(2) Material may be tested in the wrought as received configuration.

(3) Ultrasonic testing fixes the location of the void in all three directions.

(4) Where the general direction of the discontinuity is unknown, it may be necessary to test from several directions.

(5) Method of manufacture and subsequent article configuration will determine the orientation of the unfused porosity to the material surface.

b. LIQUID PENETRANT TESTING METHOD

(1) Normally used on nonferrous machined articles.

(2) Unfused porosity will appear as a straight line of varying lengths running parallel with the grain. Liquid penetrant is restricted to surface evaluation.

(3) Surface preparations such as vapor blasting, honing, or sanding may obliterate by masking the surface discontinuities, thereby restricting the reliability of liquid penetrant testing.

(4) Excessive agitation of powder in a large container may produce foaming.

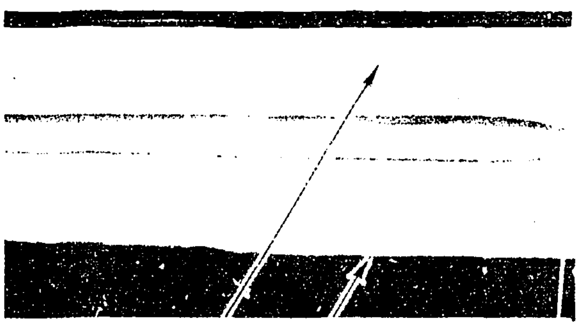
c. EDDY CURRENT TESTING METHOD. Not normally used for detecting unfused porosity.

d. RADIOGRAPHIC TESTING METHOD

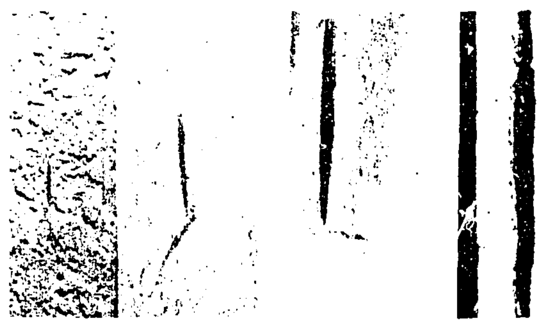
(1) Not normally used for detecting unfused porosity.

(2) Wafer-thin discontinuities are difficult to detect by a method which measures density or which requires that the discontinuity be parallel and perpendicular to the X-ray beam.

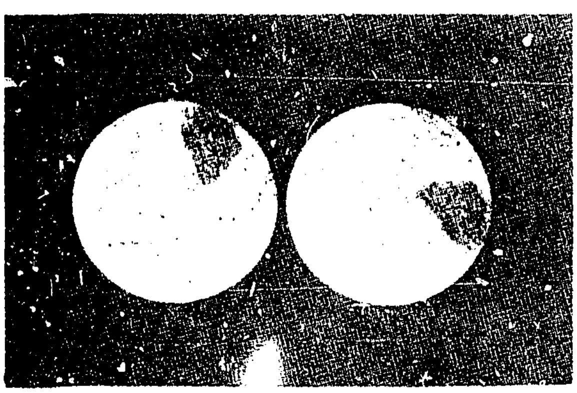
e. MAGNETIC PARTICLE TESTING METHOD. Not applicable. Material is nonferrous.



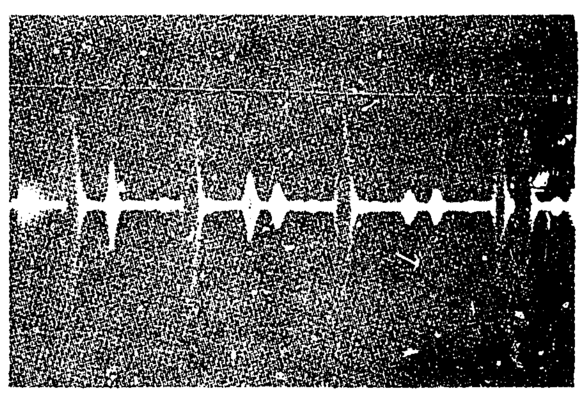
A FRACTURED SPECIMEN SHOWING UNFUSED POROSITY



B UNFUSED POROSITY EQUIVALENT TO 1/64, 3/64, 5/64 AND 8/64 (LEFT TO RIGHT)



C TYPICAL UNFUSED POROSITY



D ULTRASONIC SCOPE PATTERN OF (C)

Figure 7-26. Unfused Porosity Discontinuity

727 STRESS CORROSION

1. CATEGORY. Service

2. MATERIAL. Ferrous and Nonferrous

3. DISCONTINUITY CHARACTERISTICS

Surface. Range from shallow to very deep, and usually follow the grain flow of the material; however, transverse cracks are also possible. (See Figure 7-27.)

4. METALLURGICAL ANALYSIS

Three factors are necessary for the phenomenon of stress corrosion to occur: 1) a sustained static tensile stress, 2) the presence of a corrosive environment, and 3) the use of a material that is susceptible to this type of failure. Stress corrosion is much more likely to occur faster at high levels of stress than at low levels of stress. The type of stresses include residual (internal) as well as those from external (applied) loading.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. LIQUID PENETRANT TESTING METHOD

(1) Liquid penetrant is normally used for the detection of stress corrosion.

(2) In the preparation, application, and final cleaning of articles, extreme care must be exercised to prevent over spraying and contamination of the surrounding articles.

(3) Chemic l cleaning immediately before the application of liquid penetrant may seriously affect the test results if the solvents are not given time to evaporate.

(4) Service articles may contain moisture within the discontinuity which will dilute, contaminate, and invalid results if the moisture is not removed.

b. EDDY CURRENT TESTING METHOD

(1) Not normally used to detect stress corrosion.

(2) Eddy current equipment is capable of resolving stress corrosion where article configuration is compatible with equipment limitations.

c. ULTRASONIC TESTING METHOD

(1) Not normally used to detect stress corrosion.

(2) Discontinuities are perpendicular to surface of material and require surface technique.

d. MAGNETIC PARTICLE TESTING METHOD

(1) Not normally used to detect stress corrosion.

(2) Configuration of article and usual nonmagnetic condition exclude magnetic particle testing.

e. RADIOGRAPHIC TESTING METHOD

(1) Not normally used to detect stress corrosion.

(2) Surface indications are best detected by NDT method designed for such application. However, radiography can and has shown stress corrosion with the use of the proper technique.

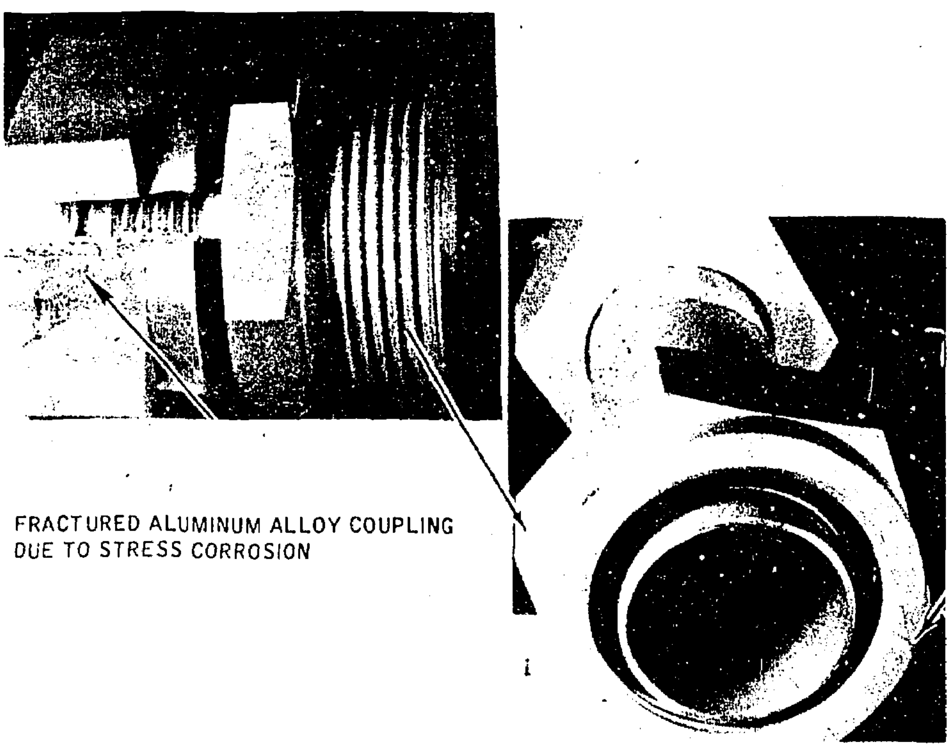


Figure 7-27. Stress Corrosion Discontinuity

728 HYDRAULIC TUBING

1. CATEGORY. Processing and Service

2. MATERIAL. Aluminum 6061-T6

3. DISCONTINUITY CHARACTERISTICS

Surface and internal. Range in size from short to long, shallow to very tight and deep. Usually they will be found in the direction of the grain flow with the exception of stress corrosion, which has no direction. (See Figure 7-28.)

4. METALLURGICAL ANALYSIS

Hydraulic tubing discontinuities are usually one of the following:

a. Foreign material coming in contact with the tube material and being embedded into the surface of the tube.

b. Laps which are the result of material being folded over and not fused.

c. Seams which originate from blowholes, cracks, splits and tears introduced in the eariler processing, and then are elongated during rolling.

d. Intergranular corrosion which is due to the presence of a corrosive environment.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. EDDY CURRENT TESTING METHOD

(1) Universally used for testing of nonferrous tubing.

(2) Heavier walled tubing (0.250 and above) may not be successfully tested due to the penetration ability of the equipment.

(3) The specific nature of various discontinuities may not be clearly defined.

(4) Test results may not be valid unless controlled by known standards.

(5) Testing of ferro-magnetic material may be difficult.

(6) All material should be free of any foreign material that would invalid the test results.

b. LIQUID PENETRANT TESTING METHOD

(1) Not normally used for detecting tubing discontinuities.

(2) Eddy current is more economical, faster, and with established standards is more reliable.

c. ULTRASONIC TESTING METHOD

(1) Not normally used for detecting tubing discontinuities.

(2) Eddy current is recommended over ultrasonic testing since it is faster and more economical for this range of surface discontinuity and nonferrous material.

d. RADIOGRAPHIC TESTING METHOD

(1) Not normally used for detecting tubing discontinuities.

(2) The size and type of discontinuity and the configuration of the article limit the use of radiography for screening of material for this group of discontinuities.

e. MAGNETIC PARTICLES TESTING METHOD. Not applicable. Material is nonferrous.

A INTERGRANULAR CORROSION

B LAP IN OUTER SURFACE OF TUBING

C EMBEDDED FOREIGN MATERIAL

D TWIN LAPS IN OUTER SURFACE OF TUBING

Figure 7-28. Hydraulic Tubing Discontinuity

729 MANDREL DRAG

1. CATEGORY. Processing

2. MATERIAL. Nonferrous Thick-Wall Seamless Tubing

3. DISCONTINUITY CHARACTERISTICS

Internal surface of thick-wall tubing. Range from shallow even gouges to ragged tears. Often a slug of the material will be embedded within the gouged area. (See Figure 7-29.)

4. METALLURGICAL ANALYSIS

During the manufacture of thick-wall seamless tubing, the billet is ruptured as it passes through the offset rolls. As the piercing mandrel follows this fracture, a portion of the material may break loose and be forced over the mandrel. As it does the surface of the tubing may be scored or have the slug embedded into the wall. Certain types of material are more prone to this type of failure than others.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. EDDY CURRENT TESTING METHOD

(1) Normally used for the testing of thin-wall pipe or tube.

(2) Eddy current testing may be confined to nonferrous materials.

(3) Discontinuities are qualitative, not quantative indications.

(4) Several factors simultaneously affect output indications.

b. ULTRASONIC TESTING METHOD

(1) Normally used for the screening of thick-wall pipe or tube for mandrel drag.

(2) Can be used to test both ferrous and nonferrous pipe or tube.

(3) Requires access from one side only.

(4) May be used in support of production line since it is adaptable for automatic instrumentation.

(5) Configuration of mandrel drag or tear will produce very sharp and noticeable indications on the scope.

c. RADIOGRAPHIC TESTING METHOD

(1) Not normally used although it has been instrumental in the detection of mandrel drag during examination of adjacent welds.

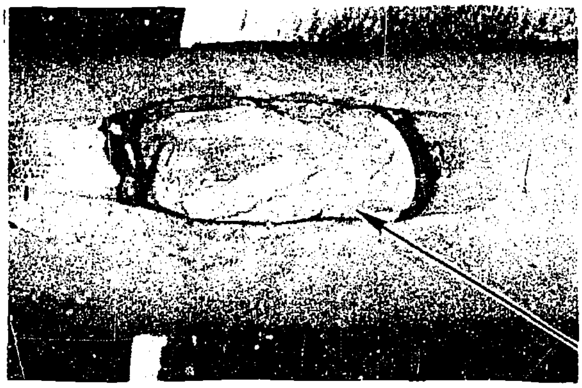
(2) Complete coverage requires several exposures around the circumference of the tube.

(3) This method is not designed for production support since it is very slow and costly for large volumes of pipe or tube.

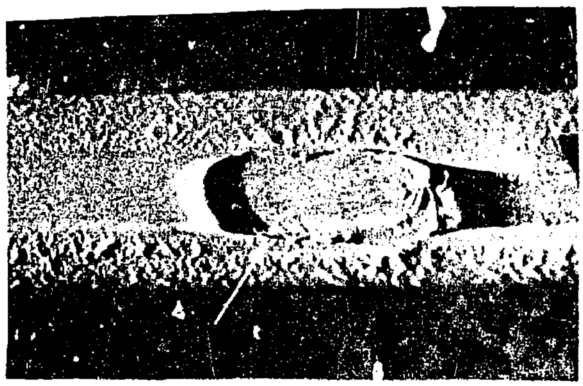
(4) Radiograph will disclose only two dimensions and not the third.

d. LIQUID PENETRANT TESTING METHOD. Not recommended for detecting mandrel drag since discontinuity is internal and would not be detectable.

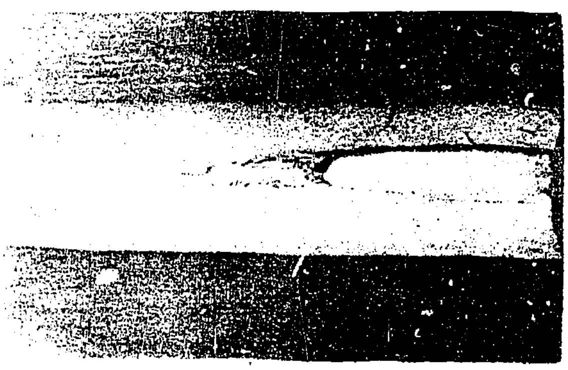
e. MAGNETIC PARTICLE TESTING METHOD. Not recommended for detecting mandrel drag. Discontinuities are not close enough to the surface to be detectable by magnetic particles. Most mandrel drag will occur in seamless stainless steel.



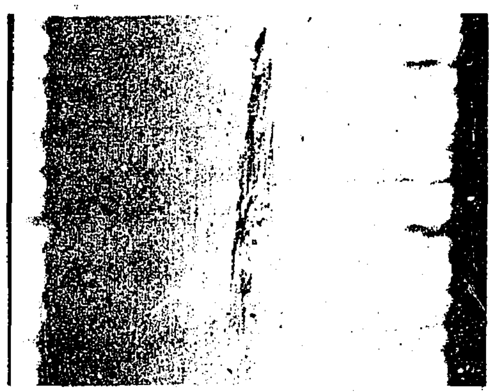
A EMBEDDED SLUG SHOWING DEEP GOUGE MARKS



B SLUG BROKEN LOOSE FROM TUBING WALL



C ANOTHER TYPE OF EMBEDDED SLUG



D GOUGE ON INNER SURFACE OF PIPE

Figure 7-29. Mandrel Drag Discontinuity

730 SEMICONDUCTORS

1. CATEGORY. Processing and Service

2. MATERIAL. Hardware

3. DISCONTINUITY CHARACTERISTICS

Internal. Appear in many sizes and shapes and various degrees of density. They may be misformed, aligned, damaged, or broken internal hardware. Found in transistors, diodes, resistors, and capacitors. (See Figure 7-30.)

4. METALLURGICAL ANALYSIS

Semiconductor discontinuities such as loose wire, weld splash, flakes, solder balls, loose leads, inadequate clearance between internal elements and case, and inclusions or voids in seals or around lead connections are the product of processing errors.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. RADIOGRAPHIC TESTING METHOD

(1) Universally used as the NDT method for the detection of discontinuities in semiconductors.

(2) The configuration and internal structure of the various semiconductors limit the NDT method to radiography.

(3) Semiconductors that have copper heat sinks may require more than one technique due to the density of the copper.

(4) Internal wires in semiconductors are very fine and may be constructed from materials of different density such as copper, silver, gold and aluminum. If the latter is used with the others, special techniques may be needed to resolve its reliability.

(5) Micro-particles may require the highest sensitivity to resolve.

(6) The complexity of the internal structure of semiconductors may require additional views to exclude the possibility of non-detection of discontinuities due to masking by hardware.

(7) Positive positioning of each semiconductor will prevent invalid interpretation.

(8) Source angle should give minimum distortion.

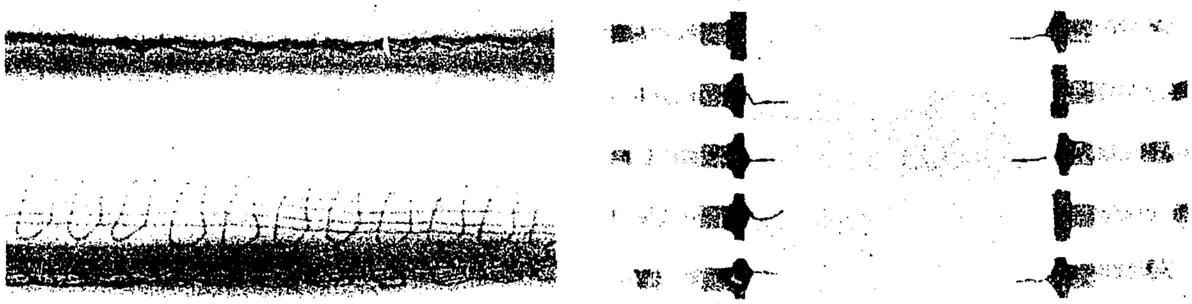
(9) Preliminary examination of semiconductors may be accomplished using a vidcon system that would allow visual observation during 360 degree rotation of the article.

b. EDDY CURRENT TESTING METHOD. Not recommended for detecting semiconductor discontinuities. Nature of discontinuity and method of construction of the article do not lend themselves to this form of NDT.

c. MAGNETIC PARTICLE TESTING METHOD. Not recommended for detecting semiconductor discontinuities.

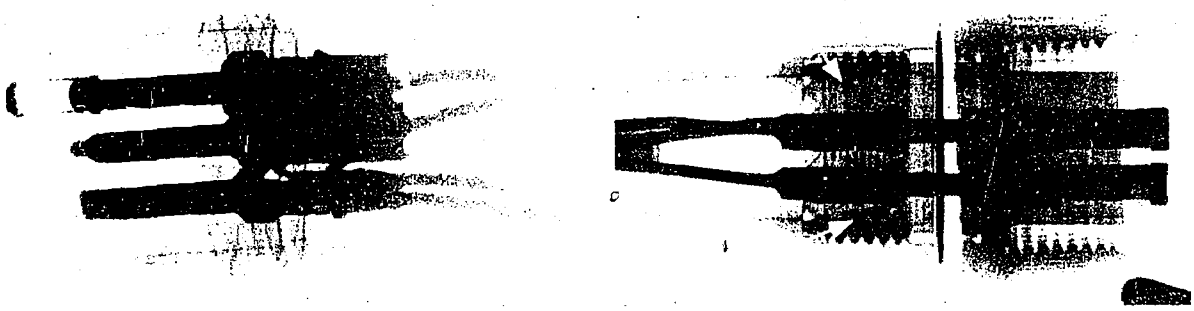
d. LIQUID PENETRANT TESTING METHOD. Not recommended for detecting semiconductor discontinuities.

e. ULTRASONIC TESTING METHOD. Not recommended for detecting semiconductor discontinuities.



A STRANDS BROKEN IN HEATER BLANKET

B FINE CRACK IN PLASTIC CASING MATERIAL



C BROKEN ELECTRICAL CABLE

D FOREIGN MATERIAL WITHIN SEMICONDUCTOR

Figure 7-30. Semiconductor Discontinuity

731 HOT TEARS

1. CATEGORY. Inherent

2. MATERIAL. Ferrous Castings

3. DISCONTINUITY CHARACTERISTICS

Internal or near surface. Appear as ragged line of variable width and numerous branches. Occur singly or in groups. (See Figure 7-31.)

4. METALLURGICAL ANALYSIS

Hot cracks (tears) are caused by non-uniform cooling resulting in stresses which rupture the surface of the metal while its temperature is still in the brittle range. Tears may originate where stresses are set up by the more rapid cooling of thin sections that adjoin heavier masses of metal, which are slower to cool.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. RADIOGRAPHIC TESTING METHOD

(1) Radiographic testing is the first choice since the material is cast structure and the discontinuities may be internal and surface.

(2) Orientation of the hot tear in relation to the source may influence the test results.

(3) The sensitivity level may not be sufficient to detect fine surface hot tears.

b. MAGNETIC PARTICLE TESTING METHOD

(1) Hot tears that are exposed to the surface can be screened with magnetic particle method.

(2) Article configuration and metallurgical composition may make demagnization difficult.

(3) Although magnetic particle can detect near surface hot tears, radiography should be used for final analysis.

(4) Foreign material not removed prior to testing will cause an invalid test.

c. LIQUID PENETRANT TESTING METHOD

(1) Liquid penetrant is recommended for nonferrous cast material.

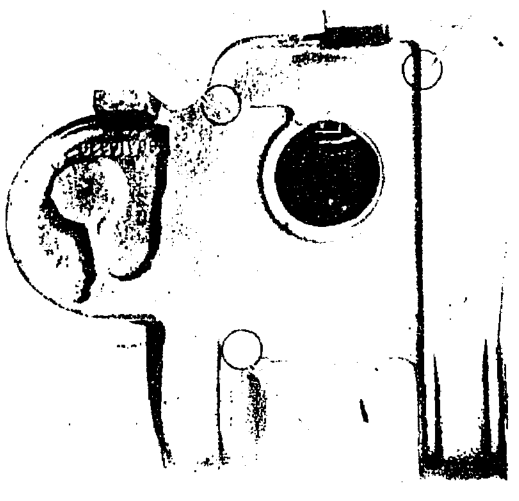
(2) Liquid penetrant is confined to surface evaluation.

(3) The use of penetrants on castings may act as a contaminant by saturating the porous structure and affect the ability to apply surface finish.

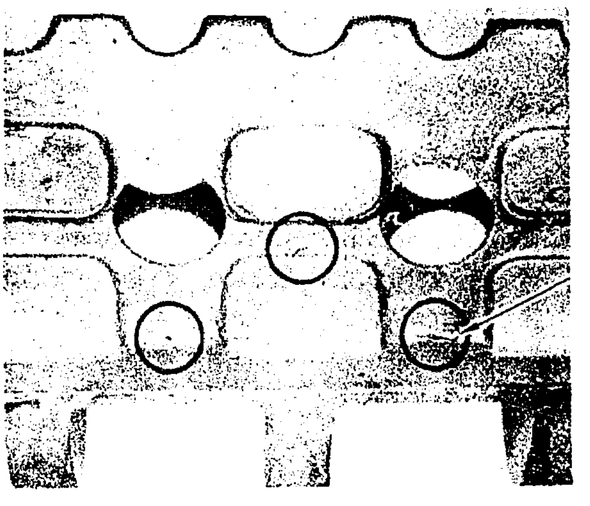
(4) Repeatability of indications may be poor after a long period of time.

d. ULTRASONIC TESTING METHOD. Not recommended for detecting hot tears. Discontinuities of this type when associated with cast structure do not lend themselves to ultrasonic testing.

e. EDDY CURRENT TESTING METHOD. Not recommended for detecting hot tears. Metallurgical structure along with the complex configurations do not lend themselves to eddy current testing.



A TYPICAL HOT TEARS IN CASTING



B HOT TEARS IN FILLET OF CASTING

C CLOSE-UP OF HOT TEARS IN (A)

D CLOSE-UP OF HOT TEARS IN (B)

Figure 7-31. Hot Tear Discontinuity

732 INTERGRANULAR CORROSION

1. CATEGORY. Service

2. MATERIAL. Nonferrous

3. DISCONTINUITY CHARACTERISTICS

Surface or internal. A series of small micro-openings with no definite pattern. May appear singly or in groups. The insidious nature of intergranular corrosion results from the fact that very little corrosion or corrosion product is visible on the surface. Intergranular corrosion may extend in any direction following the grain boundaries of the material. (See Figure 7-32.)

4. METALLURGICAL ANALYSIS

Two factors that contribute to intergranular corrosion are:

a. Metallurgical structure of the material that is prone to intergranular corrosion such as unstabilized 300 series stainless steel.

b. Improper stress relieving or heat treat may create the susceptibility to intergranular corrosion. Either of these conditions coupled with a corrosive atmosphere will result in intergranular attack.

5. NDT METHODS APPLICATION AND LIMITATIONS

a. LIQUID PENETRANT TESTING METHOD

(1) Liquid penetrant is the first choice due to the size and location of this type of discontinuity.

(2) Chemical cleaning operations immediately before the application of liquid penetrant may contaminate the article and seriously affect the test results.

(3) Cleaning in solvents may release chlorine and accelerate intergranular corrosion.

(4) Trapped penetrant solution may present a cleaning or removal problem.

b. RADIOGRAPHIC TESTING METHOD

(1) Intergranular corrosion in the more advanced stages has been detected with radiography.

(2) Sensitivity levels may prevent the detection of fine intergranular corrosion.

(3) Radiography may not determine on which surface the intergranular corrosion will occur.

c. EDDY CURRENT TESTING METHOD

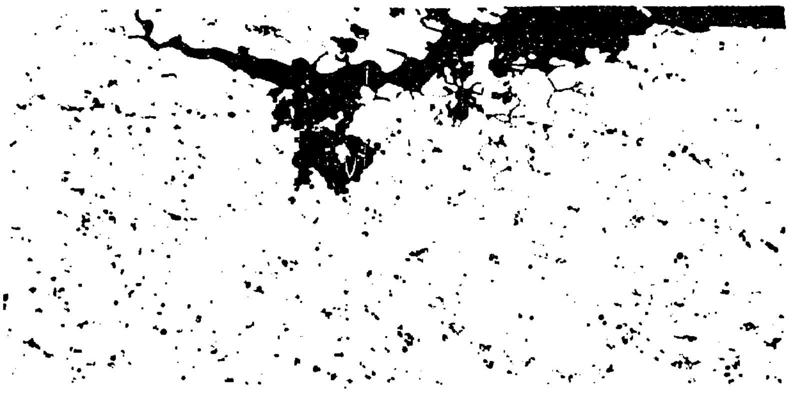
(1) Eddy current can be used for the screening of intergranular corrosion.

(2) Tube or pipe lend themselves readily to this method of NDT testing.

(3) Metallurgical structure of the material may seriously affect the output indications.

d. ULTRASONIC TESTING METHOD. Not normally used although the equipment has the capability to detect intergranular corrosion.

e. MAGNETIC PARTICLES TESTING METHOD. Not recommended for detecting intergranular corrosion. Type of discontinuity and material restrict the use of magnetic particles.



A MICROGRAPH OF INTERGRANULAR CORROSION SHOWING LIFTING OF SURFACE FROM SUBSURFACE CORROSION

B MICROGRAPH SHOWING NATURE OF INTERGRANULAR CORROSION, ONLY MINOR EVIDENCE OF CORROSION IS EVIDENT FROM SURFACE

Figure 7-32. Intergranular Corrosion Discontinuity

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