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VOLUME 2

PROCUREMENT

AN AMC QUALITY ASSURANCE REGULATION

AMC NONDESTRUCTIVE TESTING INSPECTION REGULATION

VOLUME 2

ELECTROMAGNETIC INSPECTION

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PREFACE

This is one of a series of volumes covering the field of nondestructive testing inspection used to accomplish quality assurance operations in the inspection and acceptance of Army material. As a series, these volumes constitute the Army Materiel Command's Regulation 715-501 on Nondestructive Testing Inspection.

The purpose of this volume on Electromagnetic Inspection is to provide Army Materiel Command quality assurance personnel with the basic principles underlying electromagnetic inspection techniques. The subject matter covered includes a brief history of the development of electromagnetic inspection technology, the theory and principles of electromagnetic testing and test systems, calibration and quality assurance standards, and typical applications of testing techniques. A glossary of electromagnetic testing terms and an appendix of symbolic definitions are provided for the benefit of the reader; a bibliography covers some of the more pertinent references current in the field of electromagnetic testing. It is intended that this volume serve as a reference in which answers may be found to the more general questions concerning the technical aspects and applications of electromagnetic inspection.

The information contained herein is presented in recognition of the need for increasing and enhancing the information available to engineering and inspection personnel so they may better perform their assigned duties. It is hoped that such personnel will be stimulated by this publication to seek further information in more extensive works on the subject.

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CHAPTER 1

INTRODUCTION

Section I. PURPOSE AND SCOPE

1. PURPOSE

The purpose of this publication is to provide technical guidance, information, and data to U.S. Army Materiel Command (AMC) personnel in the general field of electromagnetic nondestructive testing inspection.

2. SCOPE

a. This is one of a series of volumes on nondestructive testing inspection which, as a group, constitute the AMC Nondestructive Testing Inspection Regulation, AMCR 715-501.

b. This volume contains technical and instructional data on the testing of all types of metals, both ferromagnetic and nonferromagnetic, by means of alternating magnetic fields. Although such techniques are usually called eddy current methods, the more general term of electromagnetic testing will be used since the former fails to take into account the possibility of ferromagnetic phenomena. Electromagnetic methods, in turn, will be subclassified into magnetoinductive and eddy current methods. The former pertains to tests where the magnetic permeability of a material is the factor affecting the test results, and the latter to tests where electrical conductivity is the factor involved.

c. The term magnetoinductive has been used with a variety of meanings. For purposes of this publication, however, the term will be used to imply or refer only to the magnetism induced within a ferromagnetic material during electromagnetic testing. Static magnetic and electric methods, and very high frequency electromagnetic methods, such as X-rays, will not be covered.

d. The objectives of this volume are:

(1) To provide technical information and data regarding the availability and applicability of electromagnetic testing techniques for determining various physical properties of materials and for the detection of discontinuities and/or inhomogeneities within a material.

(2) To encourage the further use of electromagnetic testing techniques in the general quality assurance areas of design and inspection.

Section II. HISTORY

3. GENERAL

The use of electromagnetic waves for the nondestructive testing of metals outdates even the experimental proof of the reality of these waves. In 1879, the year of Maxwell's death, when many still doubted his theories, and eight years before Hertz demonstrated the existence of electromagnetic waves, D.E. Hughes was able to distinguish between different metals and alloys by means of induced eddy currents using an induction balance. Hughes' account of his experiments, published in the Philosophical Magazine of that year, is evidence of a study of surprising scope despite the crudeness of the electrical equipment then available. Lacking an electronic oscillator, Hughes used the ticking of a clock falling on a microphone to produce the exciting signals. The resultant electrical impulses passed through a pair of identical coils and induced eddy currents in objects placed within the coils. Listening to the ticks with a telephone receiver, Hughes adjusted a system of balancing coils until the sounds disappeared and noted the different adjustments needed for objects of different sizes, shapes and materials.

4. DEVELOPMENT OF TESTING TECHNIQUES

a. Observations such as those made by Hughes and others in the latter part of the nineteenth century have led to today's sophisticated instrumentation for the nondestructive testing of metal products. Looking back, Hughes' comment about the "exceeding sensitivity" of the induction balance to many different types of variables, including breathing near the coils, is particularly appropriate. There is no doubt that the electromagnetic method tended to respond sensitively to almost any type of physical change in metals. This, unfortunately, was the source of its greatest difficulties. 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, was not always quantitative in response. Efforts in the field today are largely directed toward this end.

b. While investigations of electromagnetic test methods preceded the development of practically every other modern technique of nondestructive testing, the field was a long time developing. Until recently, the electromagnetic method had only limited applications. Without provisions for discrimination between responses to different conditions (such as flaws, heat treatment variations, alloy variations, dimensional variations, internal stresses due to forming operations, and small vibrations of the part or of the test coil(s) during testing), electromagnetic tests were, at best, limited in usefulness.

c. As experience was gained in electromagnetic testing, several major breakthroughs occurred in the problem of discrimination between variables. Farrow, Zuschlag, and Foerster were individually instrumental in introducing the phase sensitive method of analysis. Foerster and his group, in particular, developed a large line of highly successful instrumentation. Later, other methods such as multiple-frequency techniques were introduced. Significant improvements also resulted from specialized coil design. Recently, transistorization of electromagnetic test equipment has resulted in the ability to produce systems of high complexity with long trouble-free lifetimes, as well as miniaturized, highly portable apparatus.

d. Today, electromagnetic testing has been developed to the stage where it can provide a rapid, accurate, and reproducible nondestructive testing inspection technique. It is compatible with electronic control circuits and, therefore, suited to automatic or semi-automatic inspection on production lines. It has served to speed up certain types of tests formerly performed visually or manually and in some cases has offered nondestructive, 100 percent inspection where only destructive sampling was previously possible. For example, tubing can now be electromagnetically tested for minute cracks and other flaws at speeds of 300 feet per minute or more, while a comparable visual inspection would usually proceed at much less than a tenth of this speed and would fail to detect flaws that were not on the surface.

e. The theories, advances, and applications of electromagnetic testing inspection form the basis for this publication.

CHAPTER 2

THEORY OF ELECTROMAGNETIC TESTING INSPECTION

Section I. GENERAL

5. GENERAL

a. Conventional electromagnetic theory is used in the general field of nondestructive testing inspection only to give qualitative assistance in explaining certain phenomena. Electromagnetic theory is used to explain (1) the generation and distribution of induced electric currents, and (2) how the change in electrical characteristics of a coil placed in the vicinity of a metallic object can be used to distinguish between geometrical, electrical, and magnetic properties of a metal. These explanations, or conclusions, have been derived from one of the few completely understood hypothetical electromagnetic test systems. This system consists of an infinitely long, straight, and circular cylinder placed in a uniform axial magnetic field (using an infinitely long cylindrical exciting coil). In practice, however, examination is limited to small regions of conductors of any shape using small coils with nonuniform fields. This means that actual testing departs widely from the idealized system for which correct, mathematical solutions exist. However, a satisfactory degree of approximation can be made experimentally for most actual cases where short bars and short test coils are used.

b. Nondestructive testing by electromagnetic (eddy current) methods involves inducing electric currents (eddy or Foucault currents) in a test piece and measuring the changes produced in those currents by discontinuities or other physical differences in the test piece. Thus, such tests can be used not only to detect flaws, but also to measure variations in test piece dimensions and resistivity. Since resistivity is dependent on such properties as chemical composition (purity and alloying), crystal orientation, heat treatment, and hardness, these properties can also be determined indirectly.

c. One method of producing eddy currents in a test specimen is to make the specimen the core of an alternating current (a-c) induction coil. There are two unrelated ways of measuring changes that occur in the magnitude and distribution of these currents. The first is to measure the resistive component of impedance of the exciting coil (or of a secondary test coil), and the second is to measure the inductive component of impedance of the exciting (or of a secondary) coil. Electronic equipment has been developed for measuring either the resistive or the inductive impedance components singly or both simultaneously (see chapter 3).

6. FERROMAGNETIC MATERIALS

The foregoing general principles apply only to nonmagnetic metals and saturated ferromagnetic materials. When an eddy current apparatus is used for testing ferromagnetic materials, the magnetic properties of the test piece influence the read-out indications and must be compensated for in interpreting the test results. When the magnetic characteristics of a material will alter the scale of the readings, sorting of materials or components will then usually rely upon differences in some other property such as electrical resistance.

7. ELEMENTARY CONCEPTS

In the following sections a few of the elementary concepts of electrical conductivity and magnetism will be considered. The electromagnetic properties of coils will be mentioned. The remainder of the chapter will be devoted to detailing the key points in the continuously unfolding field of electromagnetic testing inspection.

Section II. ELECTRIC AND MAGNETIC PROPERTIES OF METALS

8. GENERAL

Electromagnetic test equipment does not directly measure such things as hardness, crack depth, coating thickness, etc., but rather indirectly by their relationship to things that can be measured directly, such as conductivity, permeability, or a combination of both. The characteristics of a metal that are measured directly and are of importance to electromagnetic testing are discussed in the following paragraphs.

9. ELECTRICAL CONDUCTIVITY

a. An important property of metals is the ease with which electrons can flow within them, commonly referred to as conductivity. Conductivity can be expressed mathematically as the reciprocal of the electrical resistivity of a metal

$$\sigma = \frac{\ell}{R \times A} = \frac{1}{\rho}$$

where σ = conductivity (mho/unit length)

ρ = resistivity (ohm - unit length)

ℓ = length

R = resistance (ohm)

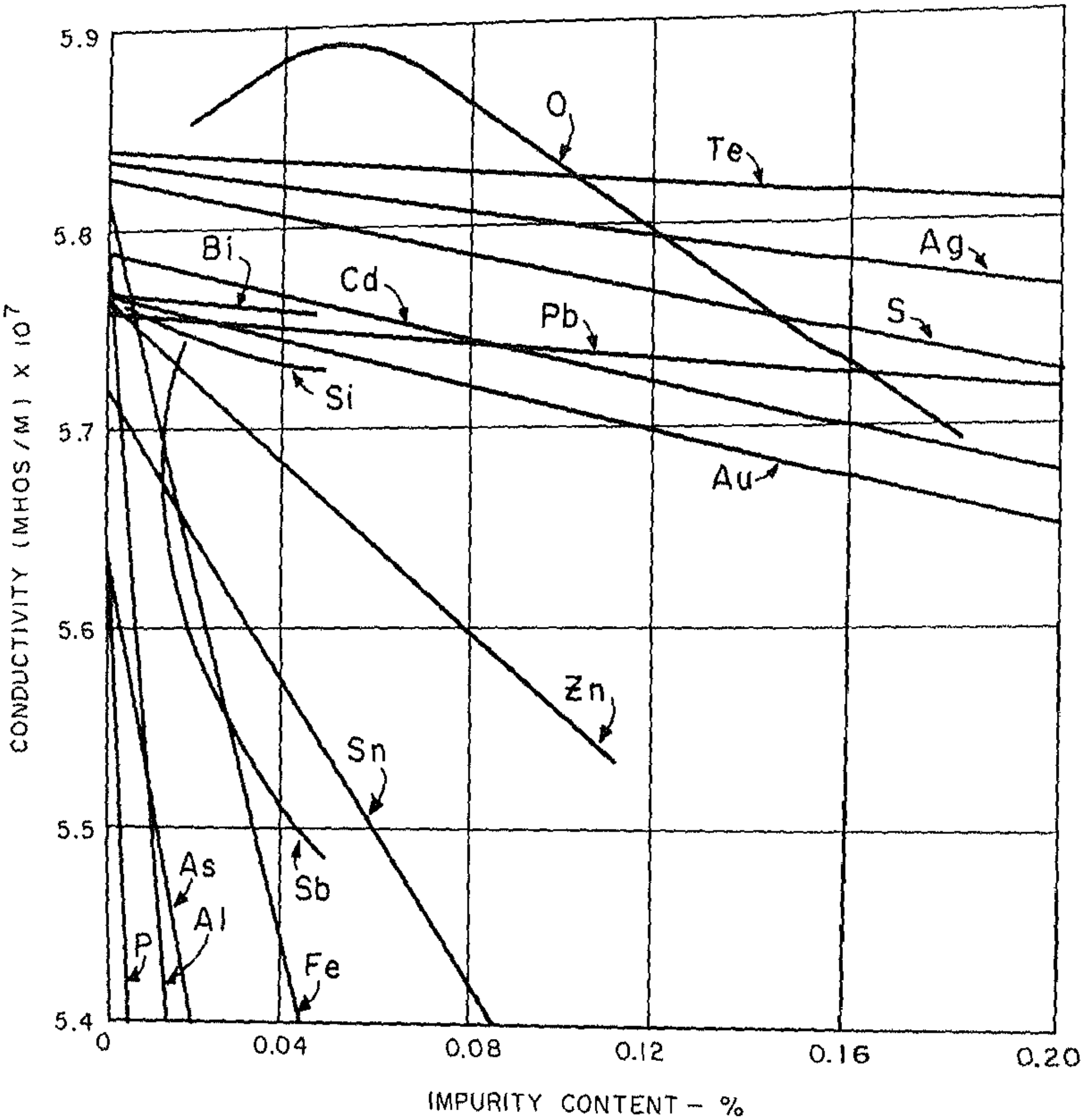
A = cross-sectional area

b. Conductivity varies widely among various metals, and a convenient means of categorizing metals is to refer to them as either conductors or nonconductors. For a pure metal, the conductivity value is unique (see table I). The addition of impurities to a pure metal will normally change its conductivity; sometimes markedly. For example, only 0.005 percent phosphorus present as an impurity in copper will decrease the conductivity from the value for pure copper by about 4 percent (fig. 1). It can be seen from figure 1 that most other impurities, as well as variations in alloy composition, also affect the conductivity of pure copper, although not as severely as phosphorus.

Table I. RESISTIVITY AND CONDUCTIVITY OF SOME METALS

Metal	Resistivity ρ (ohm-m) x 10^{-8}	Conductivity σ (mho/m) x 10^{7}	Temp. ^{o}C
Silver	1.629	6.14	18
Copper	1.692	5.91	20
Aluminum	2.63	3.8	0
Zinc	5.75	1.74	0
Iron (99.98%)	10	1	20
Platinum	10	1	20
Aluminum Bronze	12-13	0.83-0.77	0
Lead	22	0.455	20
Titanium	43.1	0.232	22
Steel (4% Si)	62	0.161	20
Bismuth	119	0.084	18
Steel (5%V, 1.1%C)	121	0.083	20

c. The current distribution within a test piece may also be changed by the presence of inhomogeneities. If a sample is perfectly homogeneous, free from flaws, and has a regularly spaced lattice, the probability of the mean free path of an electron passing through it being a constant approaches unity. A crack, slip plane, inclusion, high or low density regions, chemical inhomogeneity, cavity, or other conditions in an otherwise homogeneous material will cause a back scattering of the electron and hence shorten its mean free path. In general, a conductivity measuring device can be shown to be applicable to detecting any condition which causes the mean free path of an electron passing through it to vary by an amount lying within the measuring capacity of the device used.



GURE 1. INFLUENCE OF IMPURITIES ON THE CONDUCTIVITY OF PURE COPPER

d. If an electric wave is considered instead of electrons, the same factors impeding the flow of a single electron will impede the passage of a wave front causing it to be totally or partially reflected and/or absorbed. The various relationships between conductivity and such factors as impurities, cracks, grain size, hardness, strength, etc., have been investigated and reported in detail in the literature. Some of these relationships will be discussed later in this text.

10. MAGNETIC DOMAINS

a. Any metal placed within the region of a magnetic field will be affected somewhat. Among various metals, the individual magnetic responses vary widely, as was the case with electrical conductivity. Metals which react only slightly to magnetic fields are called either diamagnetic or paramagnetic; or more simply, nonmagnetic. Those metals which are greatly affected by the presence of a magnetic field are called ferromagnetic; or to a design engineer, magnetic. A few of the elements which display ferromagnetism are iron, nickel, and cobalt. Alloys of these metals can be made with a wide range of magnetic properties.

b. Magnetism occurs basically at the atomic level. The uncompensated, or off-balance, planetary spin of the electrons in the third incomplete shell, together with specific dimensional characteristics, creates a magnetic moment (a measure of the magnetizing force). Figure 2 is one type of an atomic model showing the inner structure of a ferromagnetic atom. This illustrates the electron arrangement necessary for the creation of magnetism. In all cases, the ratio of D (the mean diameter of the atom itself) to r (the mean radius of the unstable quantum shell) must be 3 or greater ($D/r \geqq 3$) to produce ferromagnetism. This condition is met in iron, cobalt, nickel, and in the rare earth groups (atomic numbers 58-71).

c. Magnetic moments in neighboring atoms are held parallel by quantum mechanical forces (fig. 3). These can be likened to the forces holding the sun, moon, stars, and earth in their relative positions. The probabilities of magnetism occurring in any one of six possible directions (fig. 4) are about equal. The atoms of a metal showing magnetic characteristics are grouped into regions called domains. A domain is the smallest known permanent magnet. Six thousand domains would occupy an area comparable in size to the head of a common pin. Each domain is composed of about 1 quadrillion (1,000,000,000,000,000 or 1×10^{15}) individual atoms. If each atom were the size of a half-inch ball, then a domain would contain enough of these balls to surround the earth with a band 30 miles wide!

d. In unmagnetized ferromagnetic materials, the domains are randomly oriented and neutralize each other. However, the magnetic forces are still present. Application of an external magnetic field to a metal test piece causes the randomly oriented magnetic domains to become so aligned that their magnetic moments are added to each other and to that of the applied the ς

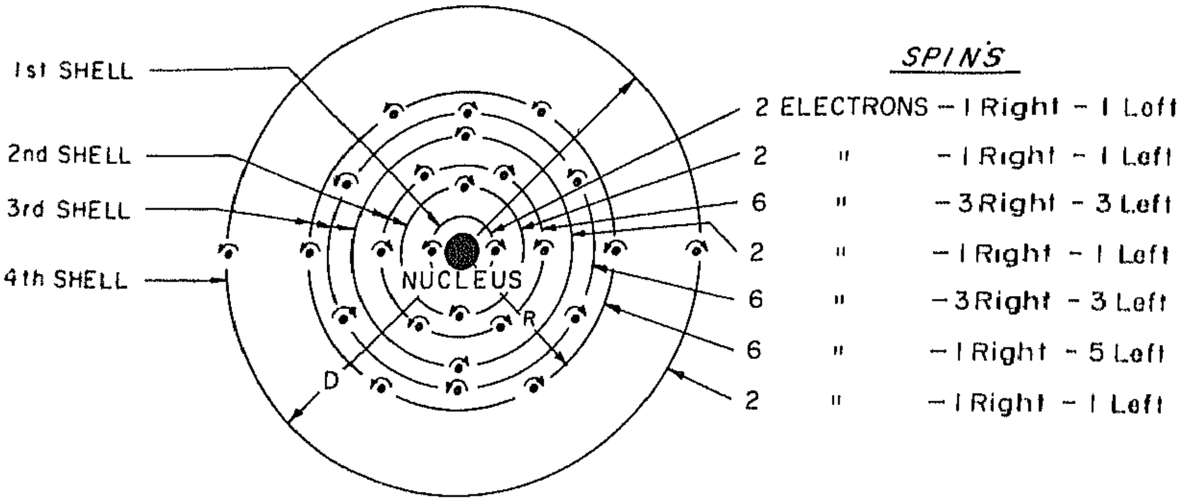


FIGURE 2. ATOMIC MODEL

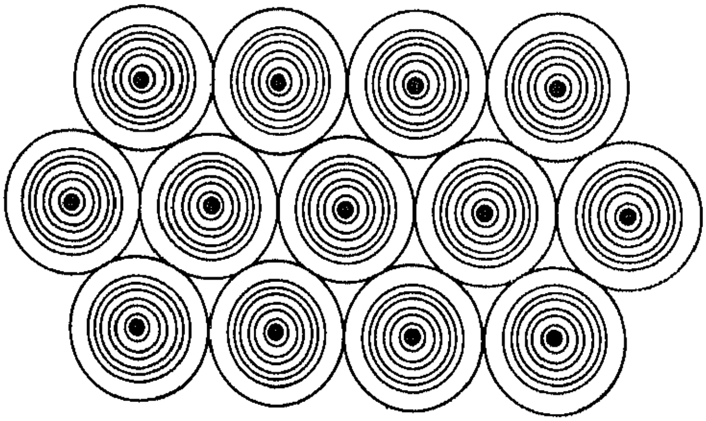


FIGURE 3. MAGNETIC MOMENTS IN NEIGHBORING ATOMS HELD PARALLEL BY QUANTUM MECHANICAL FORCES

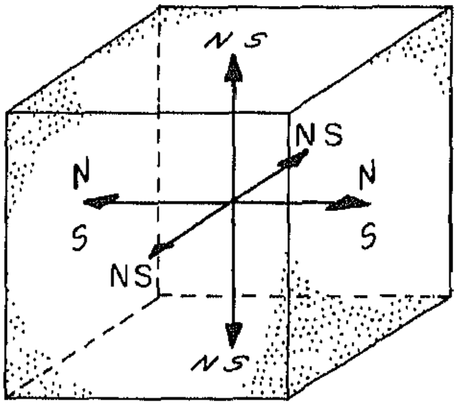


FIGURE 4. SIX POSSIBLE DIRECTIONS OF MAGNETIZATION

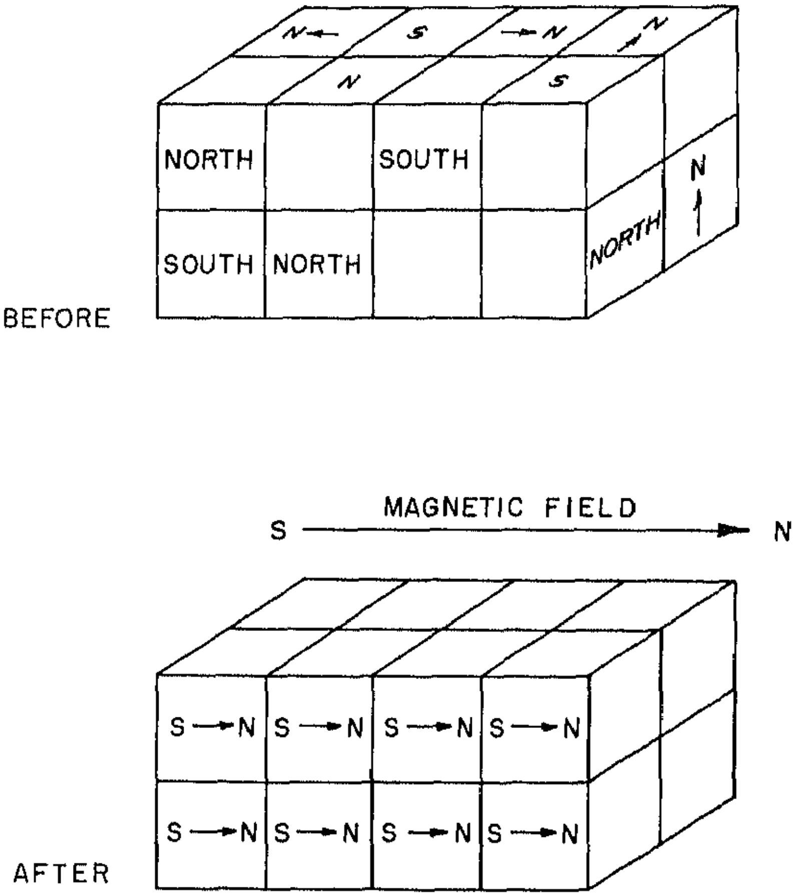


FIGURE 5. DOMAIN ALIGNMENT BEFORE AND AFTER MAGNETIZATION

field (fig. 5). With soft (weak) magnetic materials, such as iron, small external fields will result in temporary domain alignment, but, because of the small restraining force, only a little of the magnetism will be retained when the external field is removed. With hard (strong) magnetic materials, such as the Alnico alloys (aluminum-nickel-iron-alloys), a stronger external field must be applied to cause alignment of the domains; but most of this alignment will be retained when the external field is removed, thus leaving the material permanently magnetized having one major north pole and one major south pole.

11. MAGNETIC INDUCTION

a. General. The phenomena contributing to the magnetic behavior of a metal occurs at the atomic level. That is, in such materials, the net magnetic moment of all the individual atoms does not add to zero. Within a given metal, it is possible for the individual atoms to so align themselves that the net result is the creation of a strong magnetic field. It is these over-all magnetic properties of a material that are of importance to design engineers.

b. Applied and Induced Magnetism. When a magnetic material is placed in a region of an applied magnetic field (H), there is induced in that material another magnetic field (B) which may be stronger than the original applied field. As H is increased from zero, B also increases, but the relationship is not linear. A valuable piece of information to have for any magnetic aterial is a plot of B versus H; a typical curve is shown in figure 6.

c. Normal Induction. Normal induction is that characteristic magnetism luced in a metal under a given magnetizing force when the metal has been eviously demagnetized and then subjected to a sufficient number of rersals of the applied magnetizing force to bring it to a stabilized cyclic ndition, i.e., cycling of the applied force will continuously produce a able form of induced magnetic force. Figure 7 is a normal induction /H curve. It can be seen that increasing the magnetizing force H in small ncrements from the point B = 0 and H = 0, the magnetic flux B in the naterial increases quite rapidly at first, then more slowly until it reaches point beyond which an increase in H does not produce any significant ncrease in B. At this point (B max), the piece is said to be magnetically saturated.

2. MAGNETIC PERMEABILITY

a. General. Referring again to figure 6, it can be seen that there is region over which the ratio of B to H is fairly constant, and it is in this region that magnetic materials are designed to work. The constant ratio of B to H is defined as permeability (μ). Expressed mathematically:

$$\mu = \frac{B}{H} = \frac{1}{\mathcal{R} \times A}$$

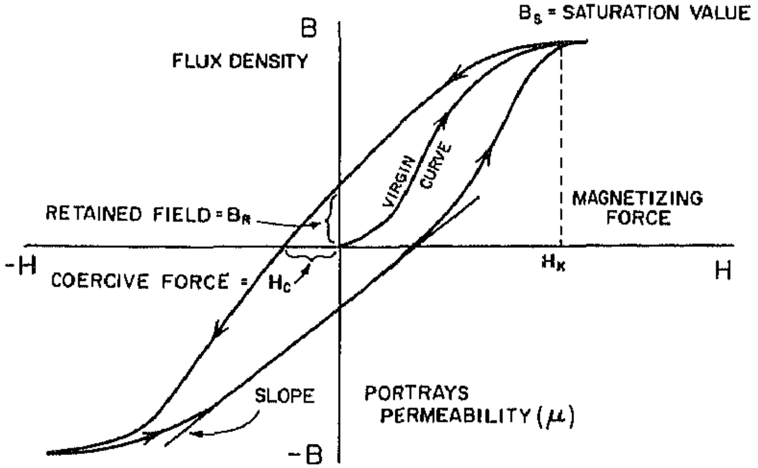


FIGURE 6. TYPICAL B/H (HYSTERESIS) CURVE

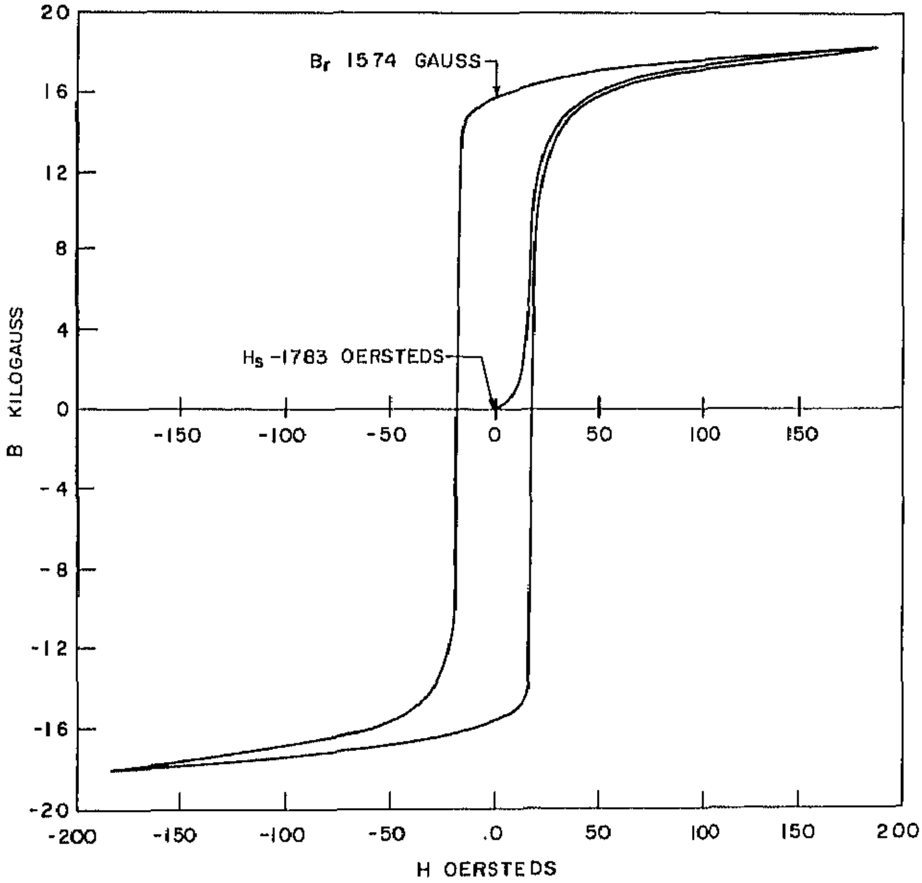


FIGURE 7. HYSTERESIS CURVE

where μ = permeability (gauss/oersted)

B = magnetic flux or induction (gauss)

H = the applied field or magnetic intensity (oersted)

the , l = length

$\mathcal{R}$ = reluctance (gilbert/maxwell)

A = cross-sectional area

Note: This expression holds only for the case in which the medium, or material, comprising the magnetic circuit is continuous; i. e., no air gaps; μ = constant.

Figure 8 shows a plot of permeability versus magnetic field intensity of the B/H curve shown in figure 7.

b. Remanence and Coercivity. An important aspect of the B versus H curve (fig. 6) is that the curve does not retrace itself when H is decreased. After magnetic saturation (B_s) has been reached, when H is decreased, B ecreases, but the B value is greater than for any previous value of H when was increasing. If H is decreased to zero, B is still finite and, in some ases, still quite high. The B field remaining after H has returned to zero, called the remanence (or retentivity) of the material, B_r. High remannce is one of the requirements of good permanent magnets. When the H ield is further reversed through zero to negative values, B decreases ntil a point is reached where it is zero. The value of the H field at this oint is called the coercive force, H_c. A further decrease in H causes he B field to become large in a negative direction until again, saturation akes place.

c. Hysteresis Loop. It can be seen from figure 6 that increasing the H field in the negative-to-positive direction produces a curve with a negative B_r and a positive H_c, and finally magnetic saturation. Thus, the curve of B versus H from a large positive H to a large negative H and back is not a single curve, but two anti-symmetrical curves which are referred to as the hysteresis loop. The area under the hysteresis loop is a measure of the work which must be expended in bringing the test sample through one cycle and is a measure of the energy loss. One criteria of a good electromagnetic core is that it has a small-area hysteresis loop.

13. EFFECT OF PROCESSING VARIABLES ON ELECTROMAGNETIC CHARACTERISTICS

a. General. Magnetization curves and hysteresis loops can be drawn for all magnetic materials to show the relationships between flux density (B) and magnetizing force (H). For each material, the characteristic shape of the curves, their amplitude, and the values of their intercepts with the axis can be altered considerably by heat treatment and mechanical

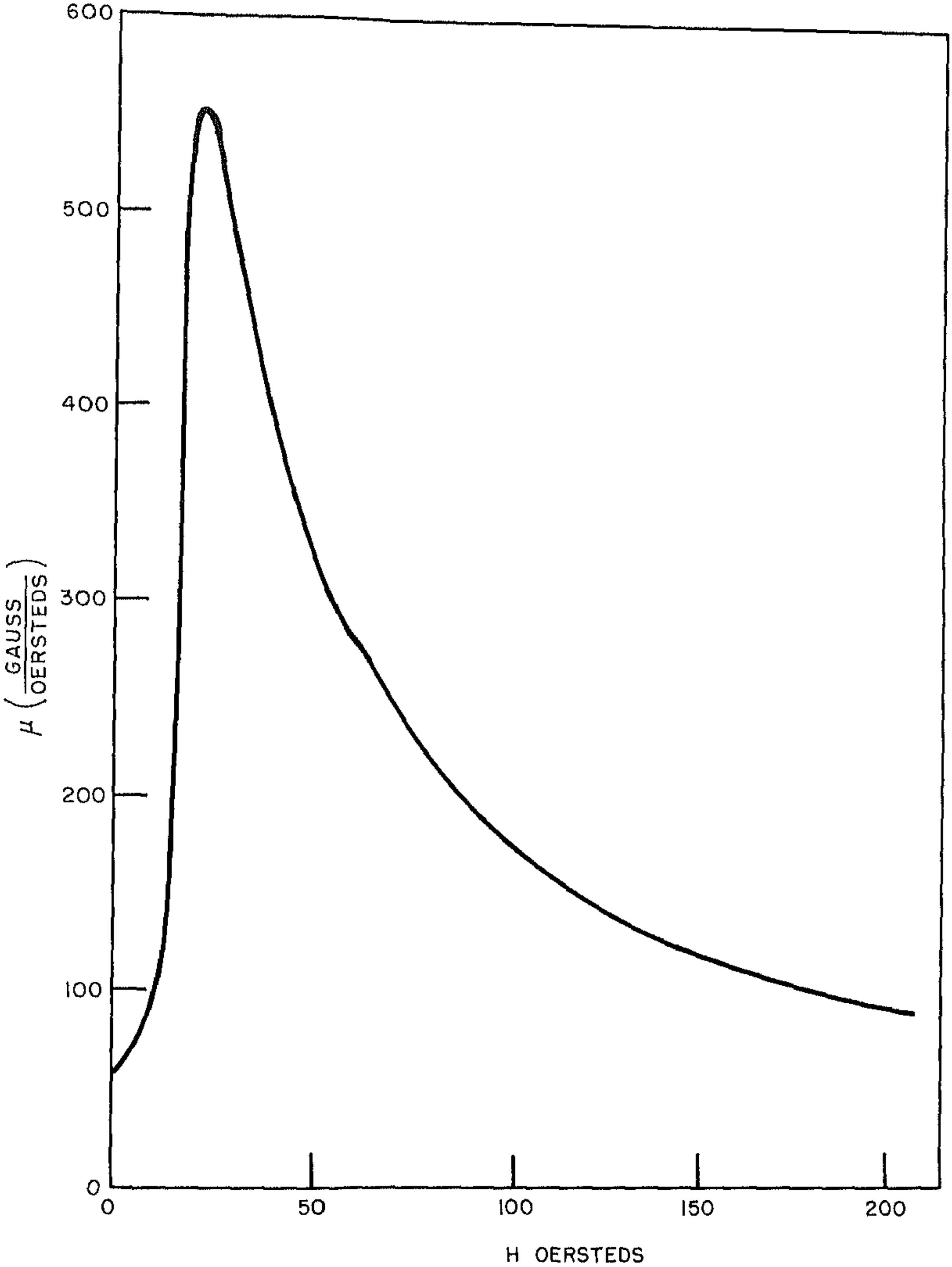


FIGURE 8. PERMEABILITY VERSUS MAGNETIC FIELD INTENSITY CURVE FROM FIGURE 7

working as well as by changing chemical composition. Sorting and comparison methods of electromagnetic testing can be based on the aforementioned curves and on the various quantities derived from them. Differences between similar materials can be shown using values of max mum intrinsic flux density (B_m), the magnetizing force (H) for fixed val of flux density, the coercive force (H_c), maximum permeability (μ_m), the values of retentivity (Br), or by measurement of hysteresis loss.

the

b. Chemical Composition. An example of the effect of chemical composition on the magnetic properties of a steel is shown in table II by the series of cobalt-chromium-molybdenum steels where the cobalt content is varied. With all ferrous materials, an increase in carbon conten increases the coercivity, resistivity, and retentivity and reduces permeability and saturation flux density. Also, there is a broadening of the hysteresis loop and an increase in the hysteresis loss value. A striking example of the effect of chemical composition on the electromagnetic properties of steel is shown by increasing the nickel content. Here, the saturation flux is greatly reduced, and at 30 percent nickel content the steel becomes completely nonmagnetic.

c. Heat Treatment. Heat treatment for steel hardening can cause th effects of variations in chemical composition to be intensified.

d. Cold Working. Cold working of ferromagnetic materials reduces the magnetic properties but gives a high value for hysteresis loss, a particularly undesirable condition in steels called upon to operate in alternating magnetic fields.

14. STRUCTURE-SENSITIVE AND STRUCTURE-INSENSITIVE PROPER

a. Some electromagnetic properties, such as saturation magnetizatio change only slowly with chemical composition and are usually unaffected by fabrication or heat treatment. However, permeability, coercive forc and hysteresis loss are highly sensitive, and show changes which are extreme among all the physical properties. Properties may thus be divided into structure-sensitive and structure-insensitive groups. As an example, figure 9 shows magnetization curves for a nickel-iron alloy after it has been (1) cold rolled, (2) annealed and cooled slowly, and (3) annealed and cooled rapidly. It can be seen that the maximum permeability (B/H) varies with the heat treatment over a wide range (up to a factor of 20), while the saturation induction (H) is the same withi a few percent. Structure-sensitive properties, such as permeability, depend on small irregularities in atomic arrangements. These irregulariti have little effect on properties such as saturation induction.

b. Some of the more common sensitive and insensitive properties are listed in table III. This table also shows the principal physical and chemical factors affecting the properties.

Table II. TYPICAL MAGNETIC PROPERTIES OF SOME METALS

Material	Saturation Flux Density (B_s)	Coercive Force (H_c)	Maximum Permeability (μ_m)	Remanence (Retentivity-B_r)	Hysteresis Loss
	Gauss*	Oersteds*	Gauss/Oersted*	Gauss*	ergs/cm^3/cycle
Commercial Nickel	5,500	5.2(B_s=10,000)	39	2,450	5,600(B=10,000)
Electrolytic Iron	10,000	2.83	1850	11,400	
Armco Iron	21,000	0.8	5000	9,000	1,000(B=5,000)
Wrought Iron	15,000-18,000	2.5	2000	7,000	
Cold Drawn Mild Steel	17,000	8-11		11,000	
Low Carbon Steel Castings	18,000	1.51	3550	10,600	
2% Ni-Cr Steel	18,200	16	432	14,000	96,000(H_m=150*)
3-1/4% Ni-Cr Steel	18,300	14.7	465	13,500	87,500
4-1/2% Ni-Cr Steel	17,500	18.5	368	13,400	102,000
1% C Steel		55		9,000	200,000
1% C, 3-1/2% Cr Steel		63		9,500	250,000
High Silicon Steel	18,000	0.6	9000	9,000	550(B=5,000)
6% W Steel		67		11,000	270,000
35% Co Steel		250		9,600	1,000,000
23% Mo Steel		250		7,000	
12% Co, 17% Mo Steel		250		10,500	1,000,000
8-80 Corrosion Resistant Steel		19	210	6,400	
Co-Cr-Mo Steels					
9%Cr, 1-1/2%Mo, 3%Co		115		7,500	
9%Cr, 1-1/2%Mo, 6%Co		135		7,300	
9%Cr, 1-1/2%Mo, 9%Co		150		8,000	
9%Cr, 1-1/2%Mo, 15%Co		180		8,600	
Gray Cast Iron	9,000-11,000	3-8	500	4,000	
White Cast Iron	9,500	12.2		5,500	

Note:
*cgs units

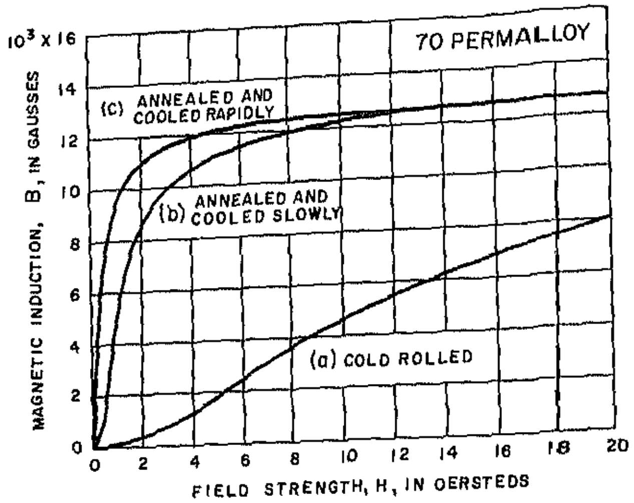


FIGURE 9. EFFECT OF MECHANICAL WORKING AND HEAT TREATMENT ON THE MAGNETIZATION CURVE OF A NICKEL ALLOY

Table III. PROPERTIES COMMONLY SENSITIVE OR INSENSITIVE TO SMALL CHANGES IN STRUCTURE, AND SOME OF THE FACTORS WHICH AFFECT SUCH CHANGES

Structure-Insensitive Properties	Structure-Sensitive Properties	Factors Affecting the Properties
Saturation magnetization	Permeability	Composition (gross)
Curie point	Coercive force	Impurities
Magnetostriction at saturation	Hysteresis loss	Strain
Crystal anisotropy constant		Temperature
		Crystal structure
		Crystal orientation

15. CHARACTERISTICS OF A MAGNETIC MATERIAL

Remanence (B_r), coercive force (H_c), hysteresis, and permeability (μ) are all characteristics of a magnetic material. Each may vary widely in different materials. In a particular material, they may also vary as a result of a number of factors. Thus, these characteristics can give some external indication of the state and condition of a material. A very close interdependence of the physical properties, electrical conductivity, and magnetic permeability exists. Any electromagnetic test system measuring conductivity is partially affected by the magnetic permeability of the specimen, particularly for depth of penetration of the excitation. This relationship is expressed by the equation:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

where δ = depth of penetration

μ = magnetic permeability ($4\pi \cdot 10^{-7}$ henry per meter for nonmagnetic materials)

f = frequency (cycles per second)

σ = volume electrical conductivity (mho per meter)

From this equation, providing the conductivity and permeability of a standard specimen is known, the frequency range can be chosen for operating the excitation field to produce maximum penetration (see par. 30). An analysis of this relationship yields a good deal of information regarding the possibilities of the general electromagnetic test methods.

16. ELECTROMAGNETIC UNITS

a. A very real difficulty is presented by the number and variety of electromagnetic test system units in use today. The most common systems are:

(1) The cgs (centimeter-gram-second) system consisting of the

  (a) practical,

  (b) esu (electrostratic units), and

  (c) emu (electromagnetic units) subsystems; and

(2) the mks (meter-kilogram-second) system which can be either

  (a) unrationalized, or

  (b) rationalized.

Rationalized means that the system has been so arranged that the factor of 4π does not appear in several of the more frequently used equations in electromagnetics, and results in simplification of the units comprising the mks system. Work on basic magnetic research has been, and still is, published in the cgs-emu system, but the rationalized mks system is favored by electrical engineers and is increasingly used in textbooks on "electricity and magnetism" at all levels. The mks system of units incorporates the practical electrical units such as the ampere, volt, ohm, joule, and watt, and eliminates the powers of 10 such as 10^7, 10^{-1}, and 10^{-8} which occur in many electrical expressions. Table IV gives the relationships between some of the more commonly used units in the various systems.

b. To illustrate how units will vary from one electromagnetic test system to another, consider the case of ferromagnetic materials whose permeability, μ, is not equal to that for free space, μ_o. The resultant flux density may be thought of as being equivalent to the sum of two components: the first being the magnetic flux density due to the applied magnetic field, and the second being the magnetic flux density due to the magnetic domains of the material (intrinsic flux density). Stated mathematically,

$$B = \mu_o H + M$$

where B is the magnetic flux density,
μ_o is the permeability of free space,
H is the magnetic field intensity, and
M is the *magnetization* or *intrinsic flux density*

The above equation can be expressed in terms of the several systems of units as follows:

$B = H + 4\pi M$	cgs - emu
$B = H + M$	cgs - practical
$B = \frac{1}{10^7} H + 4\pi M$	mks - unrationalized
$B = \frac{4\pi}{10^7} H + M$	mks - rationalized

c. A comparison of the electric and magnetic systems are given in table V. Tables VI and VII give conversion factors to be used between other units and % IACS (percent International Annealed Copper Standard).

Table IV. RELATIONSHIP BETWEEN ELECTROMAGNETIC TEST SYSTEM UNITS

		Cgs			Mks		Conversion Factors	
Quantity	Symbol	Electrostatic (S)	Electromagnetic (E)	Practical (P)	Unrationalized (U)	Rationalized (R)	Symbolic	Numeric
Length	ℓ	centimeter	centimeter	centimeter	meter	meter	$\ell_S = \ell_E = \ell_P = \frac{1}{10^2}\ell_U = \frac{1}{10^2}\ell_R$	100 cm = 1 m
Mass	m	gram	gram	gram	kilogram	kilogram	$m_S = m_E = m_P = \frac{1}{10^3}m_U = \frac{1}{10^3}m_R$	1000 gm = 1 Kgm
Time	t	second	second	second	second	second		
Force	F	dyne	dyne	dyne	newton	newton	$F_S = F_E = F_P = \frac{1}{10^5}F_U = \frac{1}{10^5}F_R$	10^5 dynes = 1 newton
Work, Energy	W	erg	erg	joule	joule	joule	$W_S = W_E = \frac{1}{10^7}W_P = \frac{1}{10^7}W_U = \frac{1}{10^7}W_R$	10^7 erg = 1 joule
Power	P	$\frac{\text{erg}}{\text{second}}$	$\frac{\text{erg}}{\text{second}}$	watt	watt	watt	$P_S = P_E = \frac{1}{10^7}P_P = \frac{1}{10^7}P_U = \frac{1}{10^7}P_R$	$10^7\ \frac{\text{erg}}{\text{sec}} = 1$ watt
Charge	Q	statcoulomb	abcoulomb	coulomb	coulomb	coulomb	$\frac{c}{10}Q_S = \frac{1}{10}Q_E = Q_P = Q_U = Q_R$	2.9979×10^9 statcoulomb = $\frac{1}{10}$ abcoulomb = 1 coulomb
Current	I	statampere	abampere	ampere	ampere	ampere	$\frac{c}{10}I_S = \frac{1}{10}I_E = I_P = I_U = I_R$	2.9979×10^9 statamp = $\frac{1}{10}$ abamp = 1 amp
Emf. Potential Diff.	E V	statvolt	abvolt	volt	volt	volt	$\frac{10^8}{c^2}E_S = 10^8 E_E = E_P = E_U = E_R$	3.3357×10^{-3} statvolt = 10^8 abvolt = 1 volt
Resistance	R	statohm	abohm	ohm	ohm	ohm	$\frac{10^9}{c^2}R_S = 10^9 R_E = R_P = R_U = R_R$	1.1127×10^{-12} statohm = 10^9 abohms = 1 ohm
Capacitance	C	statfarad	abfarad	farad	farad	farad	$\frac{c^2}{10^7}C_S = \frac{1}{10^7}C_E = C_P = C_U = C_R$	8.9874×10^{11} statfarad = 10^{-9} abfarads = 1 farad
Inductance	L	stathenry	abhenry	henry	henry	henry	$\frac{10^9}{c^2}L_S = 10^9 L_E = L_P = L_U = L_R$	1.1127×10^{-12} stathenry = 10^9 abhenry = 1 henry

Table IV (Cont). RELATIONSHIP BETWEEN ELECTROMAGNETIC TEST SYSTEM UNITS

Quantity	Symbol	Cgs			Mks		Conversion Factors	
		Electrostatic (S)	Electromagnetic (E)	Practical (P)	Unrationalized (U)	Rationalized (R)	Symbolic	Numeric
Electric Field Intensity	$\mathcal{E}$	$\frac{\text{statvolt}}{\text{cm}}$ or $\frac{\text{dyne}}{\text{statcoul}}$	$\frac{\text{abvolt}}{\text{cm}}$ or $\frac{\text{dyne}}{\text{abcoul}}$	$\frac{\text{volt}}{\text{cm}}$ or $\frac{\text{dyne}}{\text{coul}}$	$\frac{\text{volt}}{\text{m}}$ or $\frac{\text{newton}}{\text{coul}}$	$\frac{\text{volt}}{\text{m}}$ or $\frac{\text{newton}}{\text{coul}}$	$\frac{10^6}{c}\mathcal{E}_S = 10^6\mathcal{E}_E = \frac{1}{10^2}\mathcal{E}_P = \mathcal{E}_U =$ $\mathcal{E}_R$	$3.3357 \times 10^{-5}\ \frac{\text{statvolt}}{\text{cm}} = 10^6\ \frac{\text{abvolt}}{\text{cm}} =$ $\frac{1}{100}\ \frac{\text{volt}}{\text{cm}} = 1\ \frac{\text{volt}}{\text{m}}$
Magnetic Flux	ϕ	statmaxwell	maxwell	maxwell	weber	weber	$\frac{1}{c}\phi_S = \phi_E = \phi_P = \frac{1}{10^8}\phi_U =$ $\frac{1}{10^8}\phi_R$	3.3357×10^{-3} statmaxwell = 10^8 maxwells = 1 weber
Magnetic Flux Density	B	$\frac{\text{statmaxwell}}{\text{cm}^2}$	$\frac{\text{maxwell}}{\text{cm}^2}$ or gauss	$\frac{\text{maxwell}}{\text{cm}^2}$ or gauss	$\frac{\text{weber}}{\text{meter}^2}$	$\frac{\text{weber}}{\text{meter}^2}$	$\frac{1}{c}B_S = B_E = B_P = \frac{1}{10^4}B_U =$ $\frac{1}{10^4}B_R$	$3.3357 \times 10^{-7}\ \frac{\text{statmaxwell}}{\text{cm}^2} =$ $10^4\ \frac{\text{maxwell}}{\text{cm}^2} = 10^4$ gauss $= 1\ \frac{\text{weber}}{\text{m}^2}$
Magneto-motive Force	$\mathcal{F}$	statgilbert	gilbert	gilbert	$\frac{1}{4\pi}$ amp-turn	amp-turn	$\frac{c}{10}\mathcal{F}_S = \frac{1}{10}\mathcal{F}_E = \frac{1}{10}\mathcal{F}_P = \mathcal{F}_U =$ $\frac{1}{4\pi}\mathcal{F}_R$	2.9979×10^9 statgilbert $= \frac{1}{10}$ gilbert = $1\mathcal{F}_U = 79578 \times 10^{-2}\ \mathcal{F}_R$
Reluct-ance	$\mathcal{R}$	$\frac{\text{statgilbert}}{\text{statmaxwell}}$	$\frac{\text{gilbert}}{\text{maxwell}}$	$\frac{\text{gilbert}}{\text{maxwell}}$	$\frac{1}{4\pi}\ \frac{\text{amp-turn}}{\text{weber}}$	$\frac{\text{amp-turn}}{\text{weber}}$	$\frac{c^2}{10^7}\mathcal{R}_S = \frac{1}{10^8}\mathcal{R}_E = \frac{1}{10^7}\mathcal{R}_P = \mathcal{R}_U =$ $\frac{1}{4\pi}\mathcal{R}_R$	$8.9874 \times 10^{11}\ \frac{\text{statgilbert}}{\text{statmaxwell}} =$ $10^{-9}\ \frac{\text{gilbert}}{\text{maxwell}} = 1\mathcal{R}_U = 7.9578 \times 10^{-2}\mathcal{R}_R$
Magneti-zation Dipole	M	$\frac{\text{statmaxwell}}{\text{cm}^2}$	$\frac{\text{maxwell}}{\text{cm}^2}$ or gauss	$\frac{1}{4\pi}\ \frac{\text{maxwell}}{\text{cm}^2}$ or $\frac{1}{4\pi}$ gauss	$\frac{\text{weber}}{\text{meter}^2}$	$\frac{1}{4\pi}\ \frac{\text{weber}}{\text{meter}^2}$	$\frac{10^9}{c}M_S = 10^4 M_E = 4\pi \cdot 10^9 M_P =$ $M_U = 4\pi M_R$	$3.3357 \times 10^{-7}\ \frac{\text{statmaxwell}}{\text{cm}^2} = 10^4\ M_E =$ $1.2566 \times 10^5\ M_P = 1\ M_U = 12.566\ M_R$
Magnetic Field Intensity	H	statoersted	oersted	oersted	$\frac{1}{4\pi}\ \frac{\text{amp-turn}}{\text{meter}}$	$\frac{\text{amp-turn}}{\text{meter}}$	$\frac{c}{10^3}H_S = \frac{1}{10^3}H_E = \frac{1}{10^3}H_P =$ $H_U = \frac{1}{4\pi}H_R$	2.9979×10^7 statoersted $= 10^{-3}$ oersted = $1\ H_U = 7.9578 \times 10^{-2}\ H_R$
Permea-bility	μ	$\frac{\text{statgauss}}{\text{statoersted}}$	$\frac{\text{gauss}}{\text{oersted}}$	$\frac{\text{gauss}}{\text{oersted}}$	$\frac{\text{henries}}{\text{meter}}$	$\frac{1}{4\pi}\ \frac{\text{henries}}{\text{meter}}$	$\frac{10^7}{4\pi c^2}\mu_S = \frac{10^7}{4\pi}\mu_E = \frac{10^7}{4\pi}\mu_P =$ $\frac{1}{4\pi}\mu_U = \mu_R$	$8.8546 \times 10^{-16}\ \frac{\text{statgauss}}{\text{statoersted}} = 7.9578 \times$ $10^5\ \frac{\text{gauss}}{\text{oersted}} = 7.9578 \times 10^{-2}\mu_U = 1\mu_R$

Table IV (Cont). RELATIONSHIP BETWEEN ELECTROMAGNETIC TEST SYSTEM UNITS

		Cgs			Mks		Conversion Factors	
Quantity	Symbol	Electrostatic (S)	Electromagnetic (E)	Practical (P)	Unrationalized (U)	Rationalized (R)	Symbolic	Numeric
Permittivity	ϵ	Dimensionless	$\frac{\text{sec}^2}{\text{cm}^2}$	$4\pi \frac{\text{farad}}{\text{cm}}$	$\frac{1}{4\pi} \frac{\text{farad}}{\text{meter}}$	$\frac{\text{farad}}{\text{meter}}$	$\frac{c^2}{10^{11}} \epsilon_S = \frac{1}{10^{11}} \epsilon_E = \frac{1}{10^2} \epsilon_P =$ $\epsilon_U = \frac{1}{4\pi} \epsilon_R$	$8.9874 \times 10^9 \epsilon_S = 10^{-11} \frac{\text{sec}^2}{\text{cm}^2} =$ $\frac{1}{10^2} \frac{(4\pi \text{ farad})}{\text{cm}} = 1 \epsilon_U = 7.9578 \times 10^{-2} \epsilon_R$
Permeability of Free Space	μ_o	$\frac{1}{c^2}$	1 (Dimensionless)	$1 \frac{\text{gauss}}{\text{oersted}}$	$\frac{1}{10^7} \frac{\text{henries}}{\text{meter}}$	$\frac{4\pi}{10^7} \frac{\text{henries}}{\text{meter}}$	$(\mu_o)_S = (\mu_o)_E = (\mu_o)_P = (\mu_o)_U =$ $(\mu_o)_R$	$(\mu_o)_S = 1.1127 \times 10^{-21} \frac{\text{sec}^2}{\text{cm}^2}$; $(\mu_o)_E = 1$, $(\mu_o)_P = 1 \frac{\text{gauss}}{\text{oersted}}$; $(\mu_o)_U = 10^{-7} \frac{\text{henries}}{\text{meter}}$, $(\mu_o)_R = 1.2566 \times 10^{-6} \frac{\text{henries}}{\text{meter}}$
Permittivity of Free Space	ϵ_o	1 (Dimensionless)	$\frac{1}{c^2}$	$\frac{10^9}{c^2} \frac{(4\pi \text{farad})}{\text{cm}}$	$\frac{10^{11}}{c^2} \frac{\text{farad}}{\text{meter}}$	$\frac{10^{11}}{4\pi c^2} \frac{\text{farad}}{\text{meter}}$	$(\epsilon_o)_S = (\epsilon_o)_E = (\epsilon_o)_P = (\epsilon_o)_U =$ $(\epsilon_o)_R$	$(\epsilon_o)_S = 1$; $(\epsilon_o)_E = 1.1127 \times 10^{-21} \frac{\text{sec}^2}{\text{cm}^2}$, $(\epsilon_o)_P = 1.1127 \times 10^{-12} \frac{(4\pi \text{ farad})}{\text{cm}}$, $(\epsilon_o)_U = 1.1127 \times 10^{-10} \frac{\text{farad}}{\text{meter}}$; $(\epsilon_o)_R = 8.8546 \times 10^{-12} \frac{\text{farad}}{\text{meter}}$

Subscripts: S - Cgs Electrostatic

E - Cgs Electromagnetic

P - Cgs Practical

U - Mks Unrationalized

R - Mks Rationalized

Velocity of Light: $c = 2.9979 \times 10^{10} \frac{\text{cm}}{\text{sec}}$

$\frac{1}{c} = 3.3357 \times 10^{-11} \frac{\text{sec}}{\text{cm}}$

$c^2 = 8.9874 \times 10^{20} \frac{\text{cm}^2}{\text{sec}^2}$

$\frac{1}{c^2} = 1.1127 \times 10^{-21} \frac{\text{sec}^2}{\text{cm}^2}$

Constants $\pi = 3.1416$

$4\pi = 12.566$

$\frac{1}{4\pi} = 7.9578 \times 10^{-2}$

$\frac{1}{4\pi c} = 2.6545 \times 10^{-12} \frac{\text{sec}}{\text{cm}}$

$\frac{1}{4\pi c^2} = 8.8546 \times 10^{-23} \frac{\text{sec}^2}{\text{cm}^2}$

Table V. COMPARISON OF ELECTRIC AND MAGNETIC SYSTEMS

Concept	Electric System	Magnetic System
Basic Particle	Electron	Line of Flux
Symbol	e	ϕ (or J)
Units	-	maxwell
Force	Voltage or Emf	Magnetizing Force or Field Strength
Symbol	V or E	H
Units	volts	Metric: oersted English: amp-turn/inch (1 oersted=2.015 amp-turns/inch)
Flow	Current or Amperage	Flux Density or Induction
Symbol	I	B
Units	amperes	Metric: gauss English: lines/in^2 (1 gauss=1 line/cm^2=6.45 lines/in^2)
Opposition to Flow	Impedance	Reluctance
Symbol	Z	$\mathcal{R}$
Units	ohms (Ω)	gilbert/maxwell ($\mathcal{R} = \frac{H}{B} \times \frac{\ell}{A}$; where $\frac{\ell}{A} = \frac{\text{length}}{\text{area}}$)
Materials Ability to Conduct Energy	Conductivity	Permeability
Symbol	σ	μ
Units	mho/unit length	gauss/oersted ($\mu = \frac{B}{H}$)

Table VI. CONVERSION FACTORS: RESISTIVITY AND CONDUCTIVITY UNITS TO % IACS

Given N units at the left, perform indicated operation to obtain % IACS*:

From Resistivity Units (N)	To % IACS
Microhm-centimeters	$1/N \times 172.41$
Microhm - inches	$1/N \times 67.879$
Ohms (mil, foot)	$1/N \times 1037.1$
Ohms (mile, pound)	$1/N \times 9844.8 \times d$**
Ohms - centimeters	$1/N \times 1.7241 \times 10^{-4}$
Ohms - meters	$1/N \times 1.7241 \times 10^{-6}$
Ohms (meter, mm^2)	$1/N \times 1.7241$
Ohms (meter, gram)	$1/N \times 1.7241 \times d$**
Relative Resistivity	$1/N \times 100$

From Conductivity Units (N)	To % IACS
Meters (ohm, mm^2)	$N \times 1.7241$
Megmhos/centimeter	$N \times 172.41$
Megmhos/inch	$N \times 67.879$
Mhos/centimeter	$N \times 1.7241 \times 10^{-4}$
Mhos/meter	$N \times 1.7241 \times 10^{-6}$
Mhos (meter, gram)	$N \times 1.7241 \times d$**
Micromhos/centimeter	$N \times 1.7241 \times 10^{-10}$
% IACS, weight basis	$N \times 0.11249 \times d$**

Notes:

*International Annealed Copper Standard = 0.15328 ohm (meter, gram at 20°C.

**In the above tables, "d" stands for density in grams per cubic centimeter.

Table VII. CONVERSION FACTORS: % IACS TO RESISTIVITY AND CONDUCTIVITY UNITS

Given N % IACS*, perform indicated operation to obtain value in units at right:

From N % IACS	To Resistivity Units
1/N x 172.41	Microhm - centimeters
1/N x 67.879	Microhm - inches
1/N x 1037.1	Ohms (mil, foot)
1/N x 9844.8 x d**	Ohms (mile, pound)
1/N x 1.7241 x 10^{-4}	Ohms - centimeters
1/N x 1.7241	Ohm - meters
1/N x 1.7241 x 10^{-6}	Ohms (meter, mm^2)
1/N x 1.7241 x d**	Ohms (meter, gram)
1/N x 100	Relative Resistivity

From N % IACS	To Conductivity Units
N x 0.5800	Meters, (ohm, mm^2)
N x 5.800 x 10^{-3}	Megmhos/centimeter
N x 1.4732 x 10^{-2}	Megmhos/ inch
N x 5.800 x 10^3	Mhos/centimeter
N x 5.800 x 10^5	Mhos/meter
N x 0.5800 x 1/d**	Mhos (meter, gram)
N x 5.800 x 10^9	Micromhos/centimeter
N x 8.89 x 1/d**	% IACS, weight basis

Notes:

*International Annealed Copper Standard = 0.15328 ohm (meter, gram) at 20°C.

**In the above tables, "d" stands for density in grams per cubic centimeter.

Section III. ELECTROMAGNETIC PROPERTIES OF COILS

17. GENERAL

When an energized coil (fig. 10) is brought near a metal specimen, eddy currents are induced in the specimen and set up a magnetic field which acts in opposition to the original magnetic field. The impedance (Z) of the exciting coil, or for that matter any coil, in close proximity to the specimen are affected by the presence of the induced eddy currents in the specimen. The path of the eddy currents is distorted by the presence of defects or other inhomogeneities. The apparent impedance of the coil is also altered by the presence of defects in the specimen. This change in impedance can be measured and is useful in giving indications of defects or differences in physical, chemical, and metallurgical structure. Instrumentation and circuitry read-out the coil impedance. This section summarizes some of the more important points to be considered regarding the electric and magnetic properties of coils.

18. ELECTRIC PROPERTIES

a. Ignoring stray capacitances, a coil in free space (i. e., the area between conductors is free of any substance) can be represented by two parameters; its inductance, L_o, and its resistance, R_o. Also, it can be assumed that L_o takes on a new value (L) and R_o a new value (R), when the pickup coil is in the resultant field induced by the primary coil and the test specimen. The value of R_o is unimportant to electromagnetic measurements because it is a constant and, for simplicity, can be assumed to be equal to zero. On the other hand, the measured voltage depends on L_o, which itself is a function of the chance number of turns in the coil. To make the results achieved independent of construction parameters of a particular test coil, it is convenient to normalize the inductance (inductive reactance), ωL, by dividing both R and ωL by ωL_o. This will generalize results to any coil with an arbitrary number of turns. The angular frequency, ω is equal to $2\pi f$, where f is the test frequency ($\omega = 2\pi f$).

b. Disregarding stray capacitances, the self impedance Z of a coil may be written

$$Z = R + j\omega L \qquad \text{where } j = \sqrt{-1}$$

Since both the resistance and inductance of the coil are to be measured, the object is to find a functional relationship between

(1) R, ωL, and ωL_o, and the radius of the coil (c), all of which are known, and

(2) the conductivity (σ), permeability (μ), and the radius of the test bar (a), which are the unknowns (to be determined).

If only nonferromagnetic materials are considered, then μ is known and constant (equal to the permeability of free space, μ_o). This leaves only

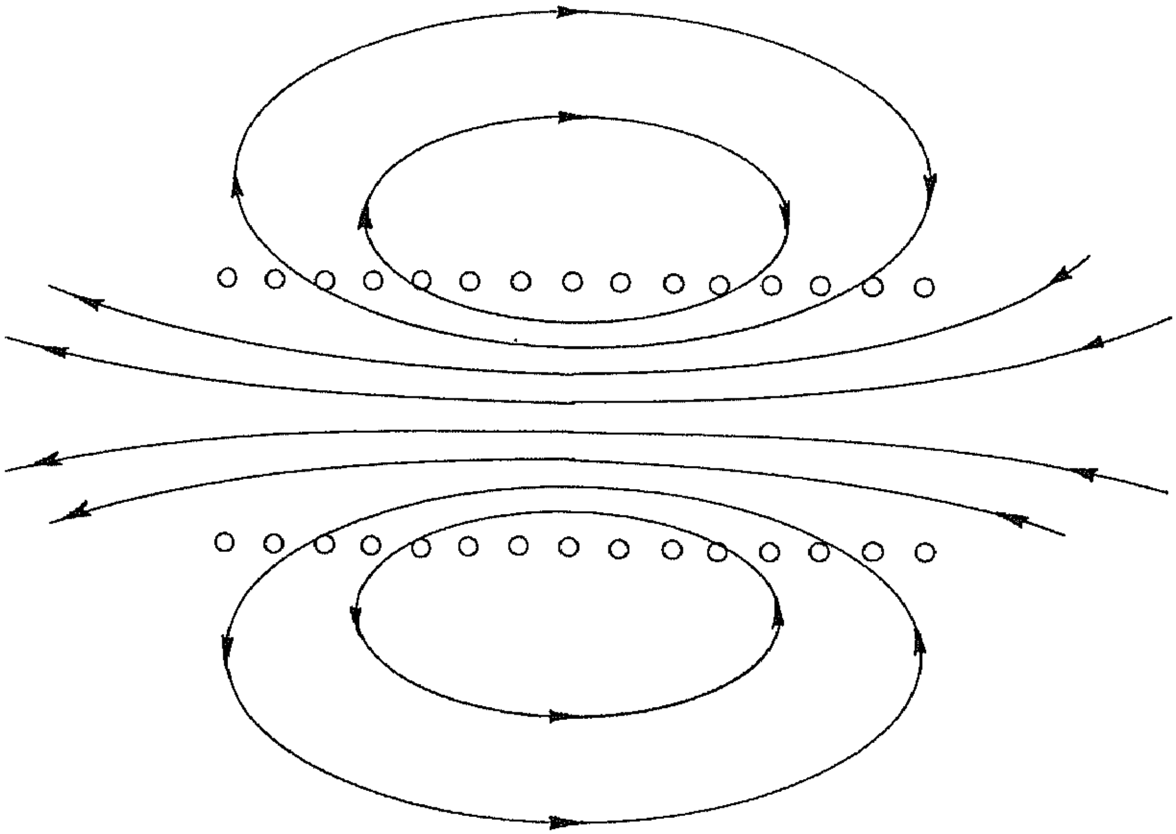


FIGURE 10. LINES OF INDUCTION SURROUNDING A SOLENOID

two unknowns, σ and a, and it is then necessary to derive two simultaneous equations involving the above parameters in which the experimental values of R and ωL uniquely determine σ and a. This derivation has been done in detail in the literature and will not be dwelt on here. However, the general technique that is used is as follows.

(1) The necessary equations are derived by solving for the resultant magnetic field and eddy currents induced in a conductor placed in the magnetic field set up by currents flowing in the coil and in the bar. The solution for any particular sample and coil geometry follows directly from *Maxwells' Equations* and *Ohms Law*.

(2) The desired equations for the resistance and inductance of the the coil under the particular geometry considered, are then obtained by integrating the resultant field over the cross-sectic of the coil.

c. In general, the following parameters of the test system affect the coil impedance:

(1) Test frequency

(2) Coupling:

  (a) Lift-off probes

  (b) Fill-factor in through-coil inspection

(3) Field strength

(4) Test coil size and shape:

  (a) Type of coil

  (b) Number and diameter of turns

  (c) Length and diameter of windings

  (d) Core material

19. MAGNETIC PROPERTIES

a. In electromagnetic testing, the applied magnetic field strength (H) is of great importance in determining the validity of a test procedure. The field strength of a system is determined by the current in the primary coil. In magnetoinductive testing, the field strength and its selection is of prime importance. *Magnetoinductive* testing is electromagnetic testing where eddy currents are present but are of no significance in the procedure:

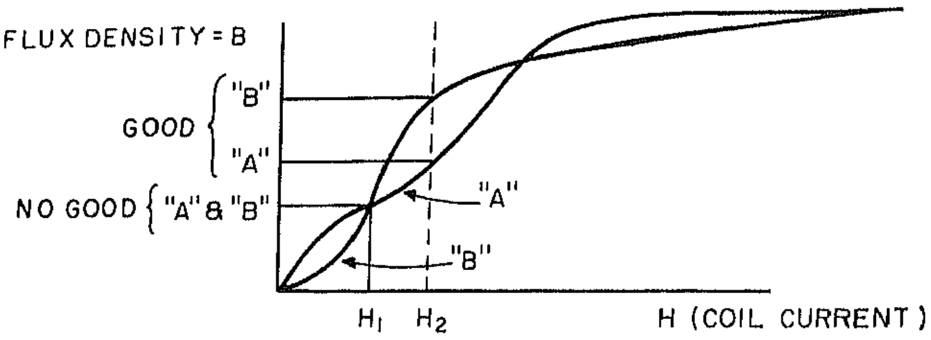
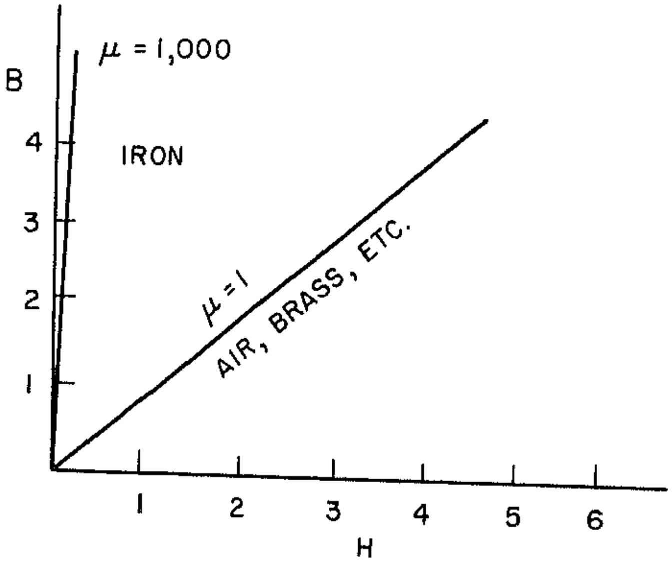


FIGURE 11. B-H RELATIONSHIP BETWEEN TWO GROUPS OF SAMPLES



GURE 12. THE PERMEABILITY OF FERROMAGNETIC MATERIALS APPROACHES UNITY WHEN MAGNETICALLY SATURATED

agnetic properties such as permeability and related variables are the rime factors. This technique is used only with magnetic metals and its rincipal application is for sorting purposes.

b. For the proper selection of the field strength, an understanding of e various B - H relationships is necessary. Applications of this concept clude:

(1) Use of various field strength levels in magnetoinductive sorting

(2) Application of d-c bias field in defect detection

(3) Nondestructive testing and evaluation of material through measurement of magnetic characteristic values

c. In magnetoinductive testing, the magnetizing current (primary coil urrent) must be set to a value which will give the greatest flux density etween groups. In figure 11, notice the relationships between the two roups A and B. If the coil current is set at point H_1, it would be mpossible to distinguish between the two groups. However, by increasi e coil current to H_2, a good separation of the two groups is possible ecause of the difference in flux densities.

d. Hysteresis curves (magnetization loops) can be plotted from data here either slowly changing direct current or continuous alternating urrent was the magnetization source (figs. 7 and 8). For magnetic aterials (iron, nickel, cobalt, or alloys containing these, such as steel e permeability value changes with variations in applied magnetizing rce. Extremely high values of magnetizing force saturate ferromagneti aterials to such an extent that the permeability (slope of the B/H curve) pproaches unity (a value of 1 - see fig. 12). This corresponds to the ermeability of nonmagnetic materials such as air, brass, plastics, etc. pplication of a very high d-c magnetic field in electromagnetic testing akes ferromagnetic materials appear nonmagnetic to the test coil. relevant permeability variations due to, for example, cold working, do ot affect eddy current coil impedance and, therefore, do not create high ackground noise.

e. When testing magnetic materials in an a-c field, increasing the eld strength (H) decreases the depth of penetration, δ (see par. 15). he decrease results from eddy current shielding. Also, the magnetic ux stays in the higher permeability zone at the surface of the test piece. high a-c magnetizing force may be used to magnetically saturate the st piece (thereby causing it to behave like a nonmagnetic material) and, t the same time, create a useful electromagnetic test signal.

Section IV. THEORY OF ELECTROMAGNETIC TESTING

20. EDDY CURRENT THEORY

The following discussion is limited to those cases where permeability (μ) is constant, and conductivity (σ) is the only variable of interest.

a. Properties of Eddy Currents

(1) Generation. In this type of testing, currents known as Foucault or eddy currents are induced in the test specimen by electromagnetic induction or transformer action. Eddy currents are a circulating current induced in a conducting material by a varying (alternating) magnetic field (fig. 13). Eddy currents are electrical in nature and have all the properties associated with electric currents. In generating eddy currents, the test piece, which must be a conductor, is brought into the field of a coil carrying alternating current. The coil may either (a) encircle the part, (b) be in the form of a probe, or (c), in the case of tubular shapes, may be wound to fit inside the tube (see chapter 3 for further details on coil design).

(2) Effect of conductivity on distribution.

(a) The original electromagnetic field of the coil is altered according to the magnitude, phase, and distribution of the induced eddy currents, and it is the effects of these currents on the impedance of the coil that is measured in all eddy current techniques. In general, the alteration of the field produced by the eddy currents is a function of:

(1) the frequency and field strength of the exciting current;

(2) coil-to-test specimen spacing (lift-off of probes; fill factor in through-coil inspection);

(3) such coil geometry factors as coil size, type and number of turns and diameter of wire, and length and diameter of windings;

(4) core material,

(5) specimen electrical conductivity;

(6) specimen magnetic permeability;

(7) specimen geometry;

(8) specimen surface irregularities;

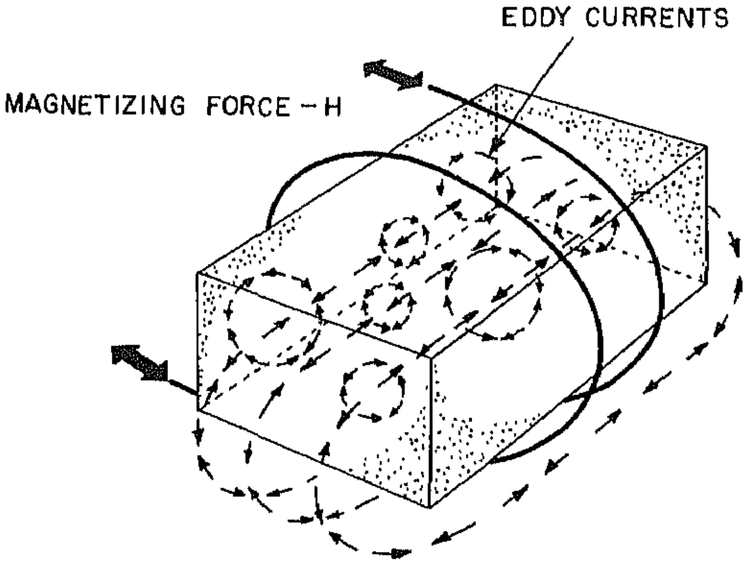


FIGURE 13. PRODUCTION OF EDDY CURRENTS BY AN ALTERNATING FIELD

(9) location of the specimen in the field of the coil; and

(10) presence and location of cracks, voids, inclusions, and composite structure of the specimen.

The eddy currents in the metal specimen also sets up its own magnetic field which opposes the original magnetic field.

(b) As stated above, the impedance of the exciting coil, or of a second coil coupled to the first, in close proximity to the specimen is affected by the presence of the induced eddy currents (this second coil is often used as a convenience and is called a sensing or pickup coil). The path of the eddy currents is distorted by the presence of a defect or other inhomogeneity. Figure 14 shows how a flaw both diverts and and crowds eddy currents. In this manner, the apparent impedance of the coil is changed by the presence of the defect This change can be measured, and is used to give an indication of defects or differences in physical, chemical, and metallurigical structure.

b. Homogeneous Distribution (conductivity, σ, is constant).

(1) Depth (skin) effect. The induced eddy currents are concentrated near the surface of the specimen resulting in the so-called skin effect.

(2) Plane conductor.

(a) In the case of a plane conductor, the current falls off exponentially with depth below the surface (fig. 15). The depth of penetration for a plane conductor was given in par. 15 as

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

Since μ and σ in this case are both constant, it can be seen that the depth of penetration becomes a function of the test frequency. 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 standard depth for several metals at various test frequencies are shown in figure 16. Charts, such as figure 16, serve as a convenient means to determine approximate depths of penetration. The diagonal lines represent the ratio of volume resistivity (in microohm-inches) to the relative magnetic permeability (μ_R) so that the effect of magnetic characteristics of certain metals may be taken into account. For nonmagnetic materials, μ_R equals unity. For example, the depth of penetration in 2S Aluminum at a frequency of 5 kilocycles per

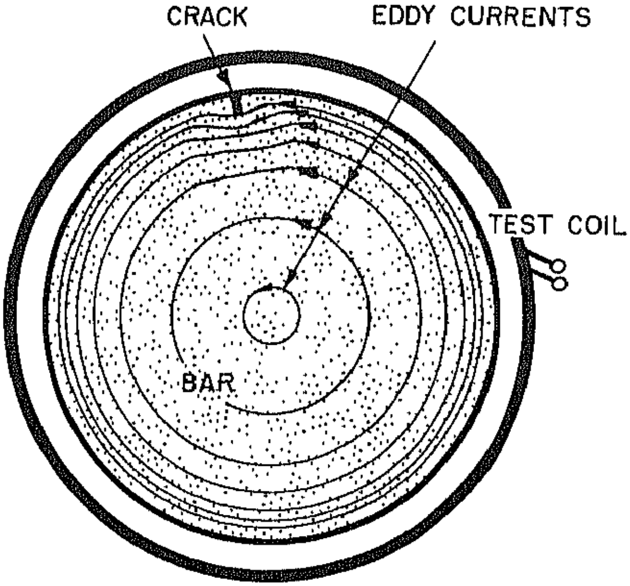


FIGURE 14. CROSS SECTIONAL VIEW OF A BAR WITH A SMALL CRACK, SURROUNDED BY AN EXCITING COIL AND A PICKUP COIL, SHOWING EDDY CURRENT DISTRIBUTION

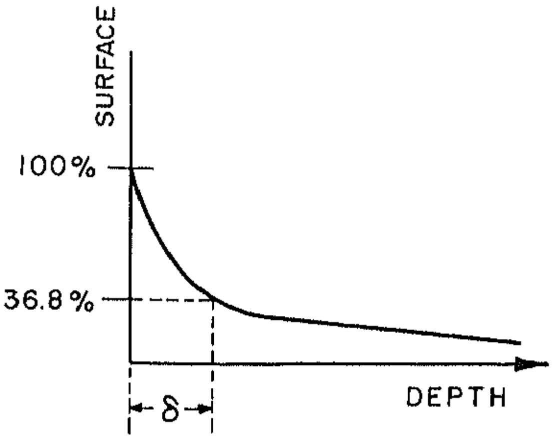


FIGURE 15. EDDY CURRENT STRENGTH DROPS OFF WITH DISTANCE FROM SURFACE

second (5×10^3 cps) may be found as shown by the dotted line in figure 16. The resitivity (ρ) of 2S Aluminum at 70°F (21°C) is 1.15 microohm-inches; the relative permeability (μ_R) for aluminum, a nonmagnetic material, is unity. Therefore, the ratio of $\rho/\mu_R = 1.15$. Following the vertical chart line corresponding to 5×10^3 cps until it intersects with the $\rho/\mu_R = 1.15$ diagonal line, the horizontal line passing through this intersection represents the depth of penetration. Following this horizontal line to the right edge of the chart, a depth of penetration of 0.048 inches is read. The range of this type chart (fig. 16) may be extended by using appropriate scale multiplying factors.

(b) The magnitude of induced eddy currents can be calculated using Faradays' law of induction. The magnitude of the induced currents as a function of depth in a media (metal specimen) is given by the following equation (it is assumed here that the magnetic field of the exciting coil varies in a single periodic manner):

$$i_2 = i_o \exp\left[-(\pi f \mu \sigma)^{\frac{1}{2}} Z\right] \exp j\left[(2\pi f t) - (\pi f \mu \sigma)^{\frac{1}{2}} Z\right]$$

where i_2 = current at depth Z
i_o = current just inside surface boundary $(Z - 0)$
f = frequency
μ = magnetic permeability
σ = electrical conductivity
Z = depth in media
j = $\sqrt{-1}$
t = time

The first exponential term in the above equation represents the <u>decrease</u> in eddy current magnitude as the depth of penetration increases. The second exponential term describes the <u>phase</u> of the eddy currents at a given depth in relation to the <u>phase</u> at the surface. The magnitude of the induced magnetic flux as a function of depth is given by a similar equation.

(c) From the foregoing equation, it can be seen that the greater the exciting frequency, conductivity, or permeability, the less the depth at which eddy currents can be induced in the metal. For nonferrous (nonmagnetic) metals whose value of permeability (μ) is unity when expressed in electromagnetic units (emu), the frequency can be chosen to achieve the desired penetration. In the case of ferrous (magnetic) metals which have a high value of μ (fig. 12), the penetration, even at very high frequencies, is small. By producing magnetic

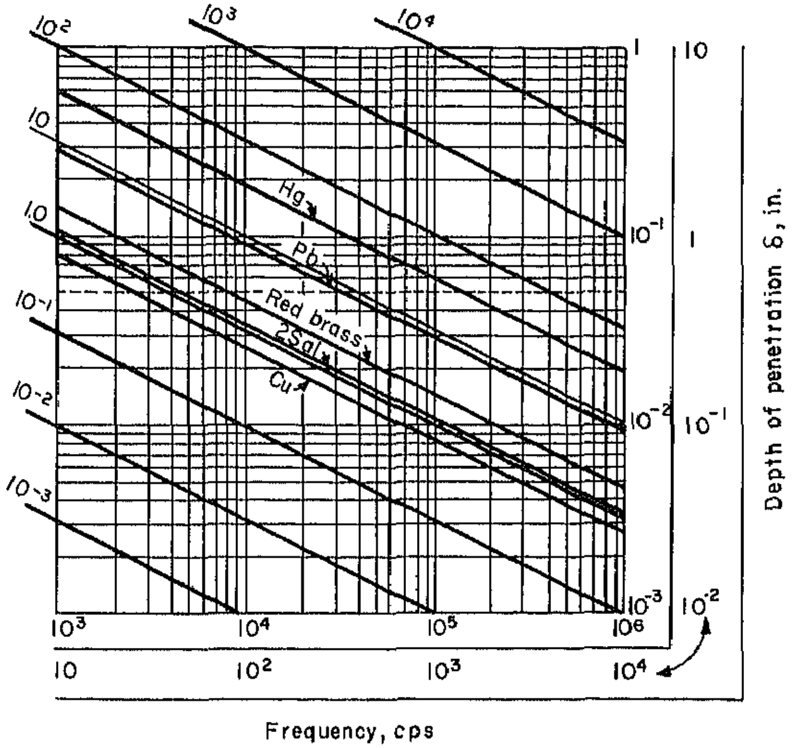


FIGURE 16. DEPTH OF PENETRATION

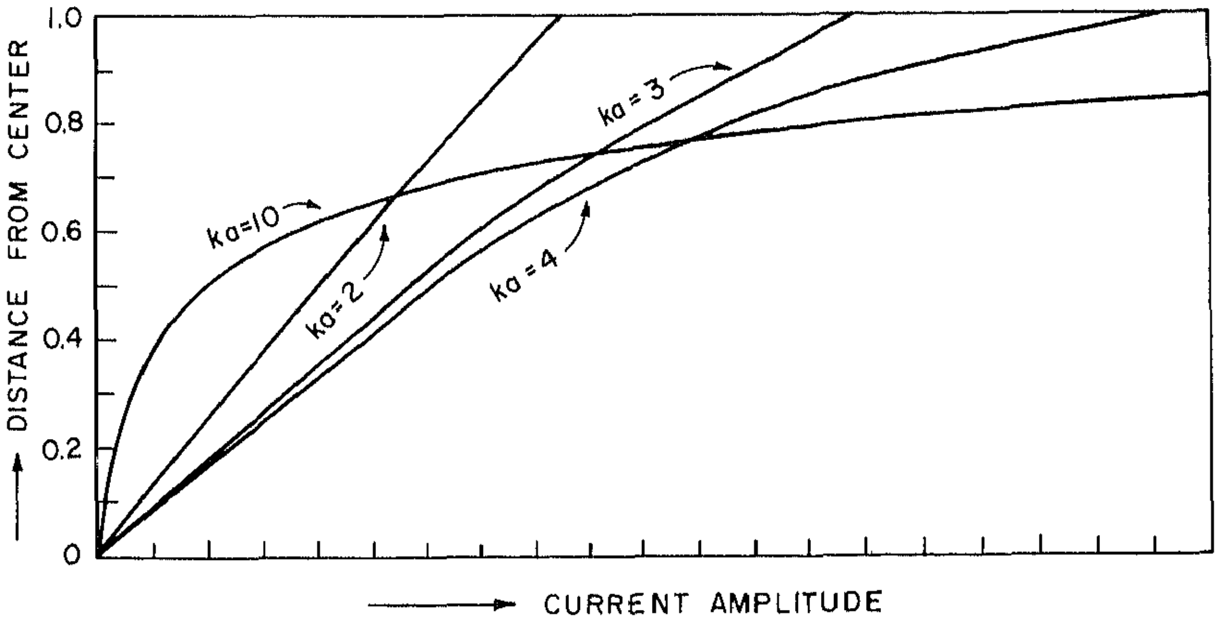


FIGURE 17. INDUCTION OF EDDY CURRENTS IN A BAR BY AN ENCIRCLING COIL

saturation in the specimen being inspected, the effective value of the permeability can be reduced. Thus, sufficient penetration is obtained to make possible eddy current inspection.

the

(3) Cylindrical specimens. The depth of penetration of eddy currents into the part being tested can be controlled by selecting the frequency of the alternating exciting field. At low frequencies, for example, eddy currents can be made to flow in the entire volume of the bar, while at very high frequencies (as illustrated by the skin effect familiar in high-frequency electric circuits) they flow only near the surface. In figure 17, the current amplitudes are plotted against radial distance from the center of the bar for four different frequencies (proportional to the square root of the ka's). The curve for the highest frequencies (ka = 10) illustrates the skin effect.

$k = \sqrt{\sigma \mu \omega}$, and a = radius of the bar

where σ = conductivity of the bar,
μ = permeability of the bar, and
ω = angular frequency (2 f)

(4) Other dimensions. So far, only the dimension of depth of penetration has been considered out of what is actually a three-dimension electromagnetic system. The other two dimensions are determined by the physical size and shape of a coil; i. e., coil geometry and field orientation. Since the exciting magnetic field is produced by an alternating current flowing through a test coil, the almost unlimited varieties of coil design afford an additional control of the test variables, and the size and extent of the test area. In testing bars, for example, coils that encircle the bar and are wide (fig. 18) are favorable for properties that are "spread-out"; e.g., overall conductivity, hardness, general porosity, or purity. On the other hand, narrow coils (fig. 19) produce what are comparatively much more sensitive responses to small flaws and local diameter variations since they restrict the region of test. Small probe coils placed on the top of the test piece (fig. 20) may be used when (a) very high sensitivity to small flows is desired, and (b) when only the region immediately below the surface is to be tested. These probe coils are also used for wall thickness measurements or whenever it is impossible to encircle the test piece with a coil.

c. Anomolous Distribution (conductivity, σ, is variable). Inhomoneities and discontinuities act to block eddy currents, diverting the rrents to flow around them. This changes the effective conductivity a test piece by crowding eddy currents into a relatively small volume. urrents cannot pass across the microscopic voids, and in being diverted

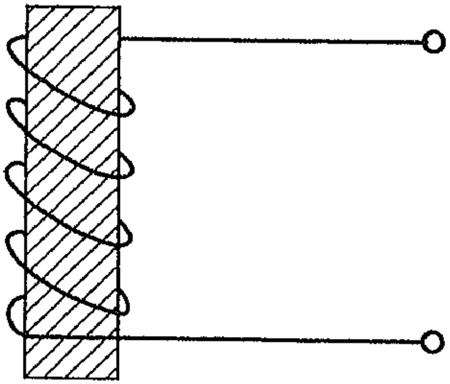


FIGURE 18. WIDE ENCIRCLING COILS FOR CONDUCTIVITY DETERMINATIONS

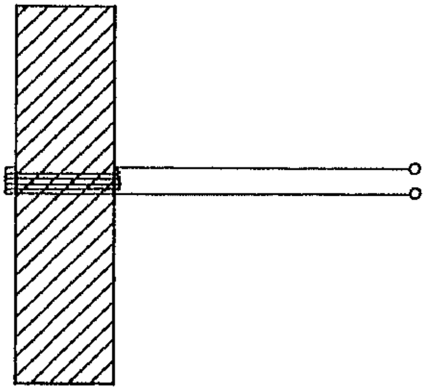


FIGURE 19. NARROW ENCIRCLING COILS FOR DETECTION OF SMALL FLAWS AND LOCAL DIAMETER VARIATIONS

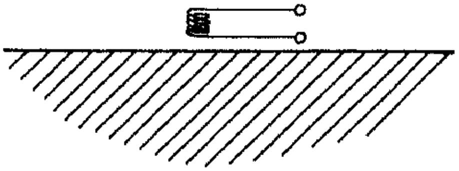


FIGURE 20. SMALL PROBE COIL FOR BEST SENSITIVITY TO SMALL FLAWS, ALSO FOR TESTING PLATES AND IRREGULARLY FORMED PARTS

around them will raise the current density in the surrounding metal, thereby lowering the effective conductivity of the specimen (see fig. 14).

21. MAGNETOINDUCTIVE THEORY

the

The preceding discussion on eddy current theory was limited to those cases where the permeability factor was assumed constant and the only variable of interest was conductivity. The following discussion will be concerned with those cases where the permeability (μ) predominates (i. e., the variable of interest). Although conductivity is also variable, in these cases, its effect on test considerations is small and is neglected.

a. Properties of Induced Magnetism (Alternating Current)

(1) General. When eddy current type apparatus is applied to ferromagnetic materials, the magnetic properties of the material frequently influence the instrument readings and must be considered in interpreting the results. The method dealing with electromagnetic tests, where permeability (μ) is the predominant variable is called the magnetoinductive method. Although the magnetoinductive (μ variable) and eddy current (σ variable) methods are similar in theory, effects due to permeability changes can be distinguished from those due to changes in conductivity. In some tests, magnetic properties merely alter the scale of readings but the test itself still depends on differences in some electrical property such as resistivity; other tests, however, depend on differences in magnetic properties. The following discussion is limited to these latter tests.

(a) Generation. The basic principle of magnetoinductive theory is intimately connected with the basic principles of eddy current testing. An alternating magnetic field is usually produced by passing an alternating current through a test coil. The object to be tested, in this case a ferromagnetic material, is then placed in or near the coil. (The specimen in eddy current testing, it will be remembered, was either nonmagnetic or magnetically saturated to behave nonmagnetically; i. e. $\mu = 1$). Here, the total energy loss will occur by two separate processes:

(1) losses due to eddy currents, and

(2) losses due to magnetic characteristics.

These two phenomena together are called core loss.

(b) Eddy current loss - see paragraph 20.

(c) Hysteresis loss - see paragraph 15.

(d) Core loss. Core loss is the combination of eddy current and hysteresis losses. In some apparatus, the change in self inductance of the coil is measured; in others, a second coil is provided and the change in the signal from this coil due to the ferromagnetic test piece is observed. The latter arrangement yields signals which are easier to interpret since they are separated from the primary signal. The results are also simplest to understand, although not necessarily the most useful or most easily produced, if the signal is so arranged as to give the actual hysteresis loop of the sample. Instead of comparing hysteresis loops one with another, a better and more useful method is to have separate coils and circuits for each sample. If two samples are compared, the trace on the oscilloscope will be a straight line if the two samples are identical. If the samples are not identical, any differences between them will produce deviations from this straight line (see chapter 3). In general, eddy current effects increase with increasing test frequencies. Therefore, most magnetoinductive testing is carried out at the lower frequencies such as 60 cycles per second.

(2) Effect of permeability on magnetic flux distribution.

(a) Eddy currents are crowded into a smaller volume when passing around flaws and discontinuities. The magnetic flux, on the other hand, is not affected in exactly the same way. The discontinuity will cause a redistribution of the flux. The largest portion of the flux will bend around the crack into the solid metal, and the remainder (a small portion) will pass through the discontinuity. In the case of a surface discontinuity, a small but detectable portion of the flux will pass outside the metal. This is called leakage flux.

(b) As shown in paragraph 15, an increase in magnetic permeability will decrease the depth of penetration of the magnetic field. This will cause a fall-off in sensitivity to subsurface flaws. The bulk of the flux distribution will then be in a small volume near the surface of the test piece.

b. Magnetic Saturation.

(1) Direct current magnetization. The term saturation is used to describe the condition of a ferromagnetic material at maximum values of magnetization. Normally, a direct current magnetic field is applied to the test part to bring it to a point where the ratio of a change in induction to a corresponding change in magnetizing force almost equals unity (i. e. , $\mu \doteq 1$). When this happens, the sample behaves like a nonferromagnetic material and irrelevant permeability variations, such as those due to cold working, will not affect eddy current coil impedance, thereby lessening the incidence of high background noise.

(2) Alternating current saturation. A high alternating current magnetizing force may be used to simultaneously saturate (magnetically) a test piece and create an eddy current signal for flaw detection equipment. This technique is especially useful for testing cold drawn material.

(3) Demagnetization.

(a) All ferromagnetic materials that have been magnetically saturated will retain a certain amount of the magnitization, called the residual field, when the external magnetizing force has been removed. This residual field may be large or smal depending on the nature of the magnetizing force applied.

(b) Demagnetization is necessary, in general, when the residual field in an object:

(1) may affect the operation or accuracy of instruments when it is placed into service;

(2) may interfere with the proper functioning of the part;

(3) might cause particles to be attracted and held to the surface of moving parts, particularly parts running in oil, thereby causing undue wear; and

(4) is likely to interfere with inspection of the part at low field strengths.

(c) In many cases, demagnetization is not required. The reasons for, and the need of, demagnetization should, therefore, be well understood so that the proper technique can be used for removal of the residual field in any given case.

(d) Several techniques can be used to demagnetize parts. One practical method is based on consideration of the character of the current used to induce the demagnetizing field. This current could be alternating current at either line frequency or at other special frequencies; it could be direct current, suitably decreasing and reversing, or accomplishing demagnetization in one decrease and reversal; it could be oscillatory in character; or it could be a combination of alternating and direct currents. A cyclic current leading the voltage can be interrupted at a predetermined point to ensure demagnetization. This is called the split-cycle method. Another method is based on the type of magnetic field used for demagnetization, with particular reference to the manner in which it is produced and in the equipment used to produce it. In this method the magnetic field can be produced by:

(1) passing current directly through the test piece.

(2) using a central conductor,

(3) use of an external winding, or solenoid, having the part to be demagnetized as its core,

(4) using a yoke, or bipolar, electromagnet, the core of which can be in the shape of a "C", or

(5) use of a monopolar electromagnet or radial field.

Many excellent references on the use of these various techniques are available.

(e) In summary, it is sufficient to say that the need for demagnetization must be determined. The proper method should be selected that will give the required degree of removal of the residual field. Finally, the proper equipment and techniques must be used to get satisfactory demagnetization.

22. THEORETICAL ANALYSIS OF ELECTROMAGNETIC TEST DATA

a. General.

(1) General. Electromagnetic theory establishes quantitatively the dependence of the resistance and reactance (R and ωL) of the test coil on the conductivity (δ) and the dimension and position of the test piece. Theory also provides a set of curves from which a measured resistive and reactive change in the test coil may be translated into a change in conductivity and/or dimensions (or conductivity and/or position) in the test piece. Prior to presenting some typical curves, useful in analyzing test data, some general terminology and brief descriptions of the terms used will be introduced.

(2) General terminology.

(a) Impedance diagram. There is an apparent change in impedance when a test coil is brought near a conductor. The reason for this apparent change is quite complicated and is affected by a large number of variables. Changes in the impedance occur in both amplitude and phase. A plot of variations in amplitude and phase of the coil impedance, which is directly related to the electromagnetic field, is known as an impedance diagram of the coil. To eliminate any dependence upon particular construction or geometry of the coil, the impedance plane graphs are normalized. This is done by using the ratio of inductance of a coil with a specimen to the inductance without a specimen (L/L_o).

(b) Characteristic frequency (f_c). Detailed investigations have shown that when impedance plane diagrams are plotted in terms of a parameter f_c, the value of this parameter can b expressed by the equation

$$f_c = \frac{2}{\pi \sigma \mu D^2}$$

where
σ = electrical conductivity in mho/meter
μ = magnetic permeability in henry/meter (equal to $4\pi \times 10^{-7}$; the permeability of nonmagnetic material)
D = sample diameter in meters

(c) The law of similarity. By using the ratio of test frequency to characteristic frequency (f/f_c), the impedance plane curves can be used for materials of any conductivity, perme bility, and diameter. In choosing a test frequency, it is onl necessary to select a value of f/f_c which lies in the linear range of the impedance plane. This is called the law of similarity.

(d) Fill factor. The fill factor (N) is equal to the ratio of the square of the diameter of a cylindrical test specimen to the square of the average diameter of the encircling coil. In probe coil testing, the effect observed in the test system output (due to a change in magnetic coupling between a test specimen and a probe coil whenever the distance of separation between them is varied) is referred to as the lift-off effect.

b. Nonferromagnetic Materials.

(1) Cylindrical specimens (encircling coils).

(a) An impedance plane diagram for a test coil encircling a solid cylindrical metal rod is shown in figure 21. In this diagram, the amplitude-phase values have been resolved into two quadrature components; the reactive component and the resistive component. These components have been normaliz to eliminate any dependence on coil configuration. The reactive axis can be related to the energy stored in the coil and specimen during each cycle of alternating current. The resistive axis can be related to the energy dissipated in the specimen during each cycle. When the specimen has zero electrical conductivity, (i.e., an insulator), no eddy currents will be induced. If the conductivity of the specimen increases to some finite value, eddy currents will be induced. This will affect the impedance of the test coil in two ways.

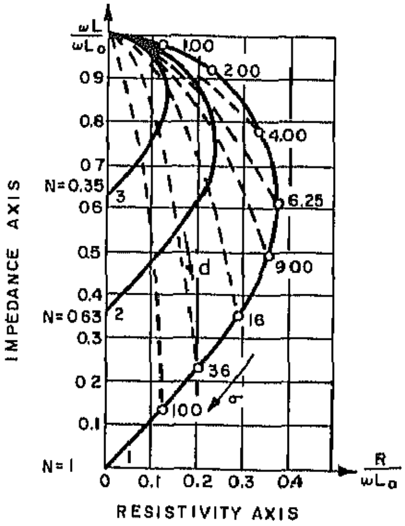


FIGURE 21. IMPEDANCE DIAGRAM FOR COIL ENCIRCLING SOLID CYLINDRICAL SPECIMEN

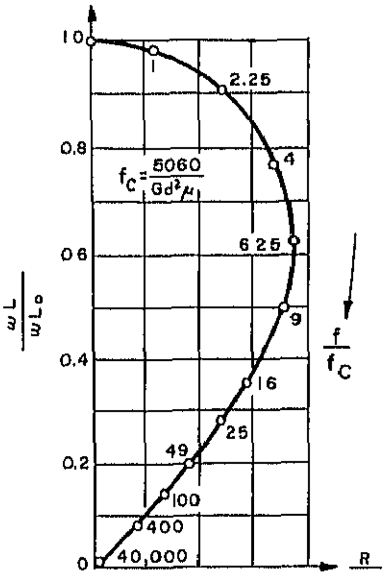


FIGURE 22. TEST IMPEDANCE IN DEPENDENCE OF f/f_c FOR NONFERROMAGNETIC MATERIALS ($\mu = 1$)

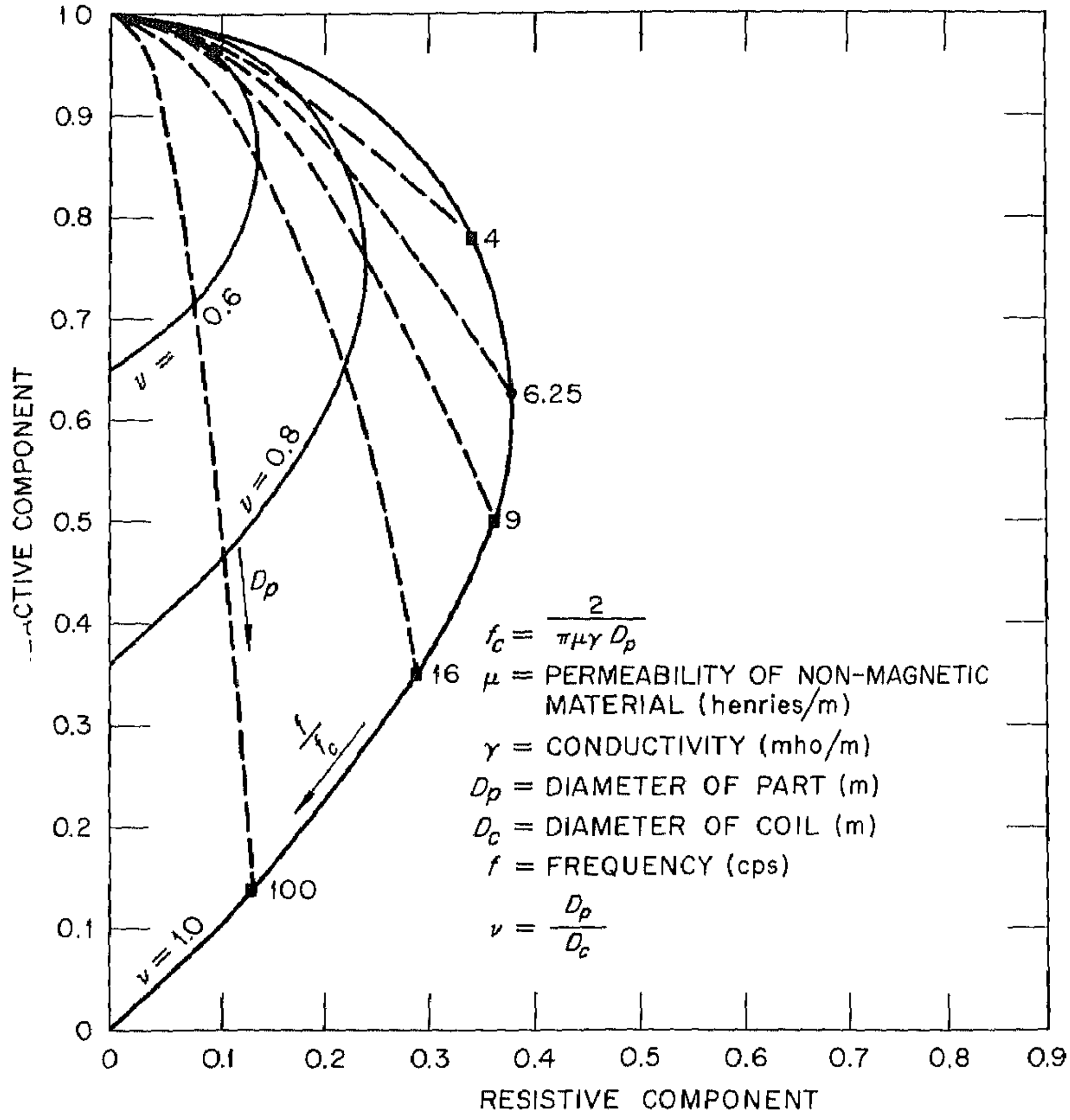


FIGURE 23. IMPEDANCE PLANE FOR COIL ENCIRCLING A METAL ROD

(1) The induced eddy currents will create their own electromagnetic field which will oppose the field of the coil.

(2) The effect of a nonmagnetic specimen is to reduce the stored energy per cycle and, at first, to increase the dissipation of energy in the form of heat. As the conductivity is further increased, the reactive component decreases; however, the resistive component first increases to a maximum, and then decreases.

The family of similarly shaped curves shown in figure 21 was obtained by varying the spacing, or coupling, between the coil and the specimen. The curves are similar in shape, differing only in size and orientation.

(b) An impedance plot for varying f/f_c ratios is shown in figure 22. In this graph, the phase between the conductivity and the rod diameter axis is essentially constant from $9 \leq f/f_c \leq 100$. By using the ratio f/f_c, this curve can be used for values of conductivity, permeability, and diameter. Figure 23 shows an impedance plane for a test coil encircling a metal rod. In this figure, the solid curves were generated by varying the f/f_c ratio for three different values of fill factor. The dashed curves represent the change in impedance resulting from a change in specimen diameter for several values of f/f_c. The dashed curves are not straight lines because the quantity f_c varies inversely with the square of the specimen diameter.

(c) There are several facts of importance regarding the impedance plane of figure 23. It should be noted that as the diameter ratio (ν) is reduced from $\nu = 1$ (the hypothetical case of equal rod and coil diameters), the size of the impedance curve decreases inversely with the square of the diameter ratio. Thus, the amount of impedance variation produced by a given change in conductivity will be reduced directly as the square of ν. Therefore, it is desirable to maintain the fill factor as large as possible to achieve the best sensitivity. Variations in diameter and f/f_c ratios produce impedance variations which, when measured from a given point in the impedance curve, occur at different phase angles. There is an angular displacement between the two effects.

(2) Plate (slab) specimens.

(a) A testing coil system commonly used to measure conductivity is the small surface-probe coil. This system is much more difficult to analyze than the encircling coil system. The probe coil is very versatile since it may be applied to a variety of shapes and sizes. The coil arrangement usually consists of one or more coils whose axes are perpendicular to the metal surface such that the current-carrying wires composing th coils are approximately parallel to the specimen surface. practical testing purposes, the use of more than one coil seldom produces an advantage over the single coil. There only the case of a single coil will be considered.

(b) There are a large number of interrelated variables which determine the impedance of a small probe coil in proximity with a metal surface. Many of these do not lend themselve readily to analytical methods. Therefore, the empirical method is most effective in studying the parameters of an eddy current probe coil system. Although the impedance variations of a probe coil in proximity with a metal sheet o finite thickness is somewhat similar to that of the encirclin type coil, mathematical analysis becomes largely impracti because of the large number of variables involved, and imp dance curves must be used entirely.

(3) Irregularly shaped specimens. In general, the radius of curva ture of a concave surface must be below a certain minimum va (e.g., 20 inches) to avoid reducing the accuracy of measurements. On convex surfaces, a minimum radius of curvature of about 4 inches can be tolerated. On round stock, a fixture should be used to ensure that the probe is placed in the same relative position on each sample.

c. Ferromagnetic Materials. The complex impedance plane for the c which a ferromagnetic test cylinder entirely fills the test coil (fill fac- or, N = 1) is shown in figure 24. It can be seen that the shape and orient ion of these curves are extensions of the curves for nonferrous materials taking into consideration the additional variable, relative permeability. In the upper portion of the graph, there is a large phase separation betwe the impedance variations caused by permeability and conductivity changes More important, however, is the fact that no ambiguity exists between conductivity (at a given frequency and permeability) and the resultant reactance, whereas the conductivity has two values for each resistive omponent value.

3. APPLICATION OF ELECTROMAGNETIC PRINCIPLES

this chapter, some of the fundamental principles of electrical conductivi nd magnetism were presented. Some of the more important aspects deal g with the electromagnetic properties of coils were discussed. The re- ainder of the chapter briefly outlined the electromagnetic theory with son sic impedance plane diagrams presented to give a broader general back- round. More detailed information on the above areas is given in the umerous references presented at the end of this pamphlet. The next chapter (chapter 3) will enumerate the various principles pertaining to such electromagnetic test systems and techniques as test coils, excitation, saturation, wave type, detection, signal handling, amplitude discriminatio phase discrimination, harmonic analysis, and signal utilization. The material presented in chapter 3 is intended to serve as a link between this chapter and chapter 4 on applications. Many of the items, such as test coils, touched on only briefly in this chapter, will be discussed in more detail in the next chapter to give a broader understanding of the applicability of electromagnetic test methods.

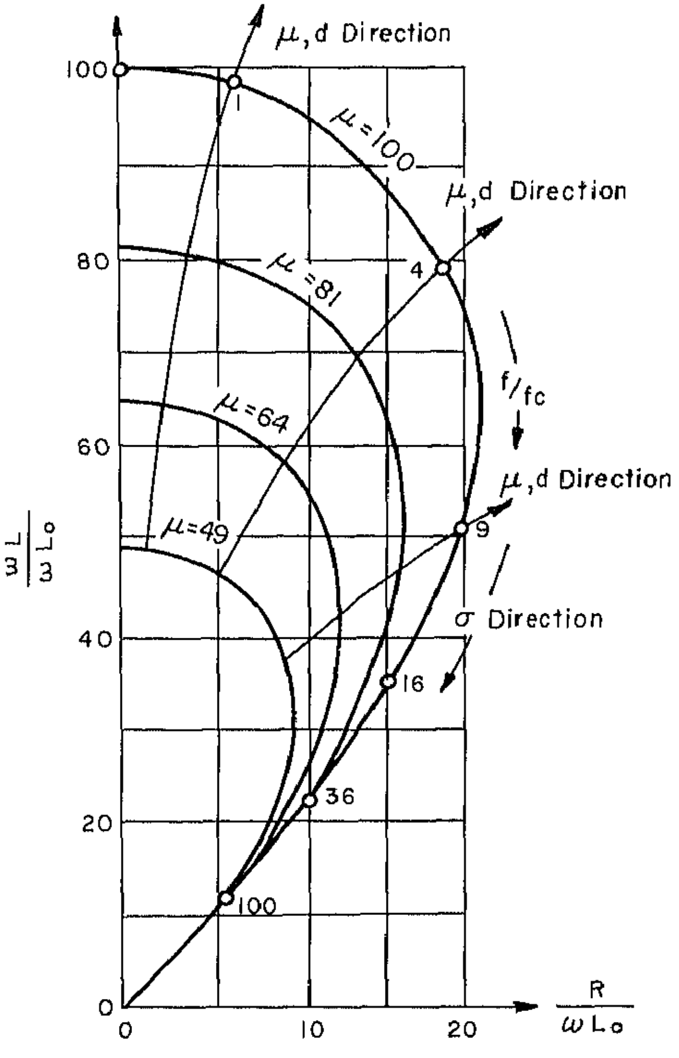


FIGURE 24. COMPLEX IMPEDANCE AND VOLTAGE PLANES FOR FERROMAGNETIC CYLINDERS WITH VARIOUS RELATIVE PERMEABILITIES (FILL FACTOR; N = 1)

CHAPTER 3

PRINCIPLES OF ELECTROMAGNETIC TEST SYSTEMS

Section I. GENERAL

24. GENERAL

a. An electromagnetic test system is actually a collection of subsystems working in conjunction with each other to extract specific data from a test. The three subsystems which generally make up the complete test systems are:

(1) the sensing elements system including both excitation and detection;

(2) the signal handling system; and

(3) the signal utilization or readout system.

When a test specimen is placed in an alternating magnetic field, certain physical effects take place. It is the function of the test system to provide the proper alternating magnetic field, detect and measure the physical effect, and to produce the desired information in some usable form.

b. A test system need not be complex or exotic; it may be quite simple. The ordinary radio broadcasting cycle can be thought of as containing all the elements of a test system. The broadcasting station uses its transmitting antenna (excitation) to generate the required alternating magnetic field. A radio uses its antenna (detection) to sense the field. The circuits within the radio amplify the high frequency signal and transform it into a low frequency signal (signal handling). The radio speaker converts the low frequency signal into the speech and music which is heard (signal utilization).

c. It has been stated that the metal test specimens may have both magnetic and electric properties. Here, metals are classified into two broad categories: ferromagnetic and nonferromagnetic. The test systems are classified in a similar manner. Test systems which measure the magnetic properties of a metal will be referred to as magnetoinductive, and those systems measuring the electrical properties of a metal will be called eddy current systems.

25. MAJOR CONSIDERATIONS

a. Test systems are usually designed to fulfill a particular need. The factors which determine the choice of a system are just as important as the test system itself. In selecting or designing a test system, certain determinations must be made to ensure that the correct system is bein applied on a particular problem. The following are examples of some of the questions which must be answered.

(1) Is the test material ferromagnetic or nonferromagnetic?

(2) For what condition or property is the material to be examine (e.g., cracks, alloy composition, heat treatment, thickness, etc.)?

(3) Does the condition or property of interest cause a change in either (a) conductivity for nonferromagnetic materials, or (b) conductivity and/or permeability for ferromagnetic materials?

b. In this chapter, each subsystem will be dealt with both individuall and as an integral part of the complete test system, with the emphasis o sensing systems and coils. Since the signal-to-noise ratio determines the feasibility of solving a given problem with a particular test system, it will be discussed in some detail. Also, some typical test problems and their solution by proper instrumentation will be given.

Section II. SUBSYSTEMS

26. SENSING ELEMENTS

a. General.

(1) The function of the sensing elements is to generate a suitable alternating magnetic field and to detect the physical reactions caused by the field. In a discussion of sensing elements, an understanding of the inherent properties of coils is of prime importance as they are related to electromagnetic testing.

(2) The simplest form of coil, and the one most widely used as a sensing element, is the solenoid. If a solenoid is connected across an a-c line, a current will flow through the wire that forms the solenoid. This alternating current will cause an alternating magnetic field to be set up around the coil (fig. 25). This points up two very important properties associated with coils.

(a) An a-c current flowing in a conductor will set up an alternating magnetic field around the conductor, and

(b) any conductor placed in an alternating magnetic field, will have circulating currents (eddy currents) induced in it (refer back to fig. 10).

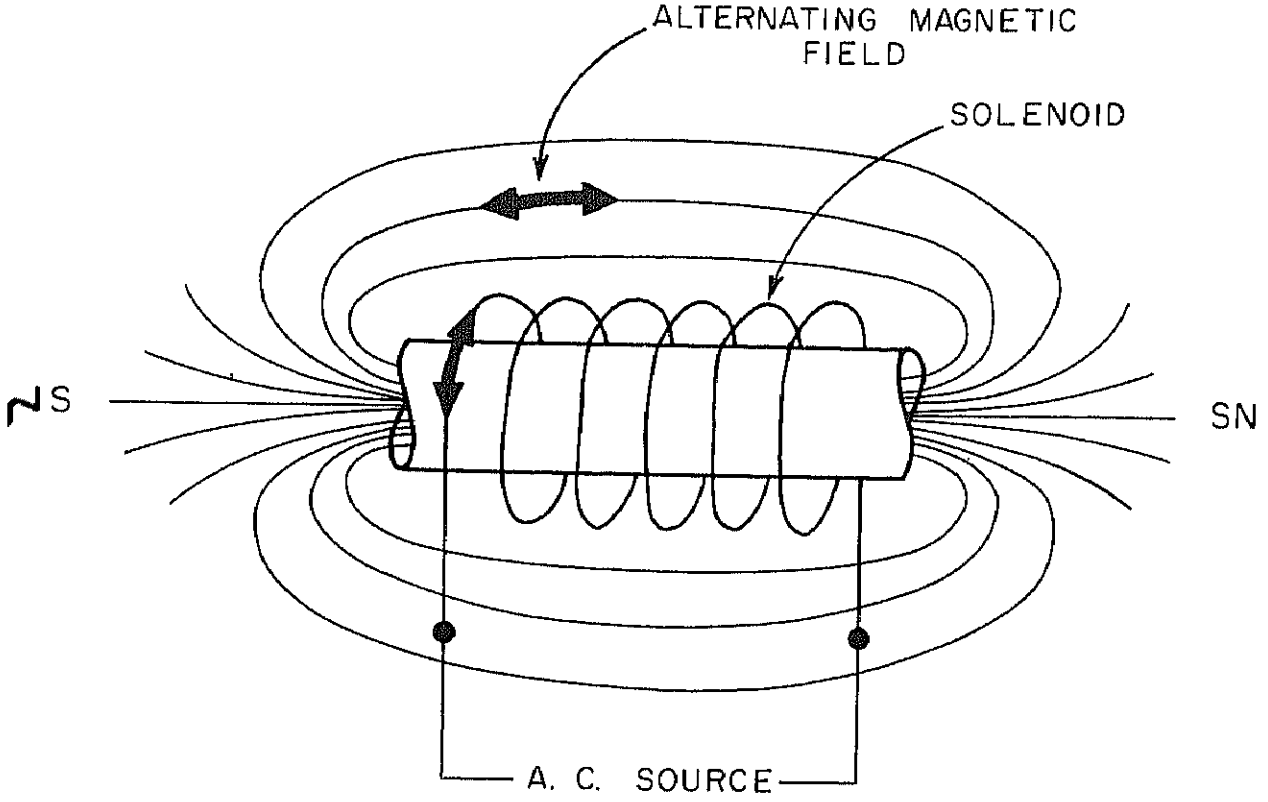


FIGURE 25. SOLENOID COIL SHOWING MAGNETIC FIELD AROUND COIL

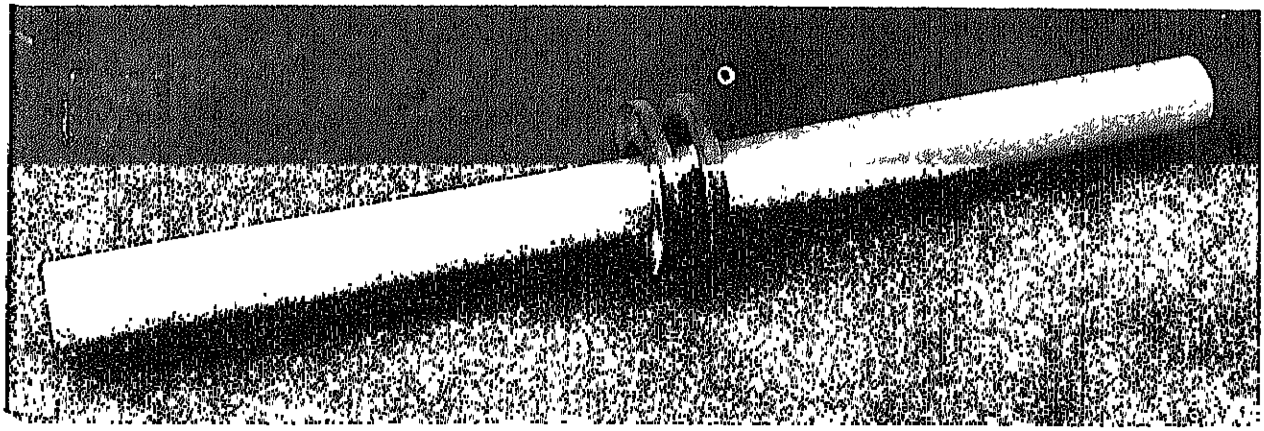


FIGURE 26. METAL BAR IN ENCIRCLING COIL

The magnitude and direction of the alternating magnetic field is not the same for all coils. The coil parameters and the frequency and magnitude of the applied a-c current will determine the properties of the alternating field.

(3) The significant property of a coil is its impedance (Z). Impedance is a rather involved principle. It is a measure of the coils opposition to current-flow through it, and is affected by many things. If a metal specimen is introduced into the magnetic field of a coil, eddy currents set up in the metal will alter the coils magnetic field, thus causing a change in the coils impedance. This change in impedance is a measurable quantity. How it is measured is shown in section III of this chapter. The question to be considered here, however, is what actually causes the coils impedance to change and how it changes.

b. Coil Operation.

(1) To illustrate the actions which take place in sensing elements, consider the case of a solenoid wound with a primary winding for excitation and a secondary winding for detection. A cylindrical aluminum specimen is then inserted into the coil. In practice, the secondary is wound on a form (usually micarta or some similar material), the primary is wound on top of the secondary, and the whole structure is placed in an enclosed case. Figure 26 shows the solenoid coil in its finished form with the metal specimen in position. The sequence of events that now takes place is as follows:

(a) an alternating current is supplied to the primary winding of the solenoid coil;

(b) the alternating current in the primary creates an alternating magnetic field;

(c) the alternating magnetic field induces a voltage in the secondary windings, and induces circulating currents (eddy currents) in the aluminum specimen;

(d) eddy currents in the aluminum specimen create their own alternating magnetic field which partly cancels the field created by the current in the primary winding of the coil;

(e) the interaction of the two alternating magnetic fields affects the electrical characteristics of the coil, called impedance; and

(f) suitable instrumentation reads-out the coil impedance.

Since the density of currents that are induced in the aluminum are a function of the aluminum's properties (i.e., alloy, hardness, heat treatment, grain size, etc.), the sequence of events described above converts the material properties of interest into an electronic signal. The reason for this becomes clear when it is realized that all the properties mentioned affect the conductivity of the aluminum; in turn, the conductivity of the aluminum controls the density and distribution of the eddy currents.

(2) Metals have been grouped into two broad categories: nonferromagnetic and ferromagnetic. The aluminum specimen used in the example is a nonferromagnetic material. The foregoing sequence of events would be changed if a ferromagnetic material, such as steel, were placed in the solenoid coil. Steel, like aluminum, exhibits a conductivity variation when one of its properties(e.g., alloy hardness) changes. In addition, steel will exhibit a change in permeability for changes in properties. Since permeability is a magnetic quantity, it is reasonable to expect that it would have some effect on the coil's operation. The conductivity and related eddy current effects are substantially the same as outlined in the sequence of events for the aluminum specimen. The additional effect of permeability variation found in steel specimens causes a change in the coil inductance which results in a variation in the coil impedance. The instrumentation monitoring the secondary coil takes an algebraic summation of the variations in coil impedance caused by changes in conductivity and permeability. It is evident that ferromagnetic materials complicate the test procedure by adding another quantity to the coil impedance. Hence, there is a need to separate the test systems into two distinct types. Table V (chapter 2), shows a comparison of the quantities used in nonferromagnetic (eddy current) systems and ferromagnetic (magnetoinductive) systems.

c. Types of Coils.

(1) The sensing elements are the key factors in eddy current systems. The coils which make up the sensing elements must be capable of producing a measurable change in their characteristics which can be related to a change in the test objects' properties. Since test objects come in many shapes and sizes, it can be expected that sensing elements will also come in various arrangements. Some considerations which affect the choice of coil types are:

(a) shape of specimen - rod, tube, sheet, etc.;

(b) type of discontinuity or variable - crack, void, heat treatment, etc.;

(c) speed and percentage inspection required;

(d) location of discontinuity or variable - surface, subsurface, inside diameter, outside diameter, etc.; and

(e) suitability of local as opposed to overall test depending on whether the discontinuity or variable can be found at all points on the test object or as a random occurrence.

(2) The most common types of sensing elements used in eddy curr test systems are:

(a) feed-through encircling coils, in which test objects such as rods, tubes, rolled shapes, wire, and other objects are passed through a hole within the test coil (fig. 27),

(b) inside diameter (ID) test coils, which are inserted within cavities such as the interior of tubes or drilled holes (fig. 2 and

(c) probe or surface coils which are placed on the surface of test objects (fig. 29).

d. Advantages and Disadvantages of the Three Types of Coils.

(1) For the feed-through coil, the advantages are its ability to: (a) evaluate an entire circumference at one time; (b) function at speeds of ten to one thousand feet per minute; and (c) not wear out easily. Its disadvantages include: (a) its inability to identify the point on the circumference containing the discontinuity; (b) at least one end of the part must be accessible; and (c) the information derived from the coil is subject to changes in mass, etc.

(2) The advantages of an ID coil are: (a) it can evaluate long tube which cannot be checked optically; and (b) it can be used at hig speed. Its disadvantages include: (a) its inability to work on curved surfaces; and (b) wear problems.

(3) The advantages of the probe or surface coil are: (a) it permit fast testing of a localized zone; (b) it is excellent for evaluatio of characteristics area of a part; and (c) it can be used where space for testing is limited. Its disadvantages include: (a) its slow test speed when an entire part must be scanned; (b) "lift o from a surface can create a measurement problem; and (c) "ec effects" create a measurement problem on small parts.

Test Coil Arrangements. Test coils may be arranged in various ns to produce different measurement effects. The most common of se arrangements are:

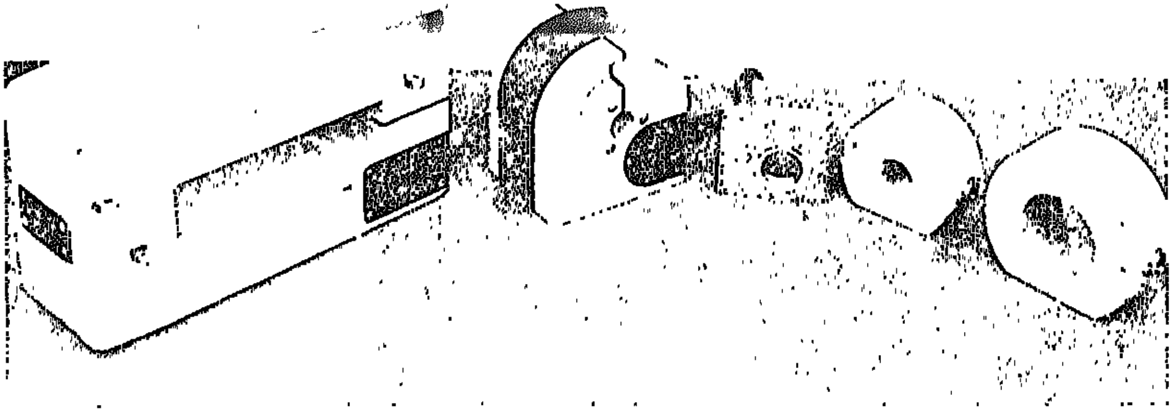


FIGURE 27. TYPES OF ENCIRCLING COILS USED IN COMMERCIAL EQUIPMENT

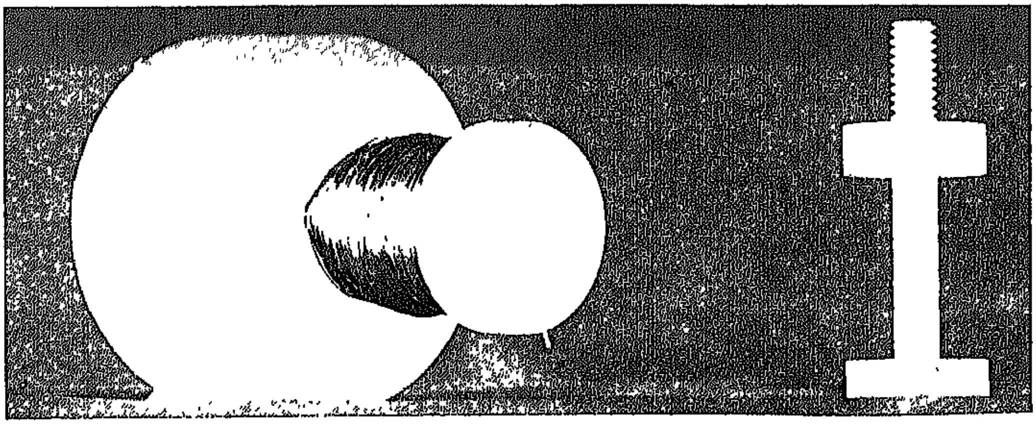


FIGURE 28. EXPERIMENTAL PROBE COILS - INSIDE DIAMETER

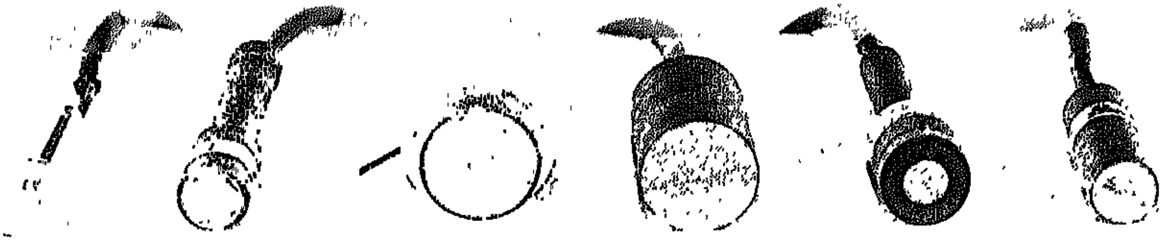


FIGURE 29. COMMERCIAL SURFACE PROBES - OUTSIDE DIAMETER

(1) resonance-circuit methods, in which the test coil is part of resonant circuit within the test system;

(2) differential coil arrangements with a reference coil (in this method, the voltage measured from a coil containing the obj to be inspected is compensated by the voltage of a second co containing a standard test object - see figure 30); and

(3) self-comparison, differential coil arrangements in which tw coils located at two points on the same specimen compare o portion of the test object with another portion of the test obj (fig. 31).

27. SIGNAL HANDLING

a. The signal handling portion of a test system is the most difficult understand. Signal handling circuits must select the desired informati from the bulk change in coil characteristics (impedance) caused by vari tions in the test object. For example, the coils scanning an aluminum will undergo impedance changes caused by variables (heat treatment, g size, etc.) which are of no concern to the test. To complicate the prob further, coil impedance changes for variables of no interest may be gr than the changes produced by variables which are of interest such as cr or other defects. Signal handling circuits must, therefore, be selective as well as sensitive when unrelated variables influence measurements. The three major quantities upon which signal handling circuits operate are amplitude, phase, and frequency. By using these three quantities i different combinations, test information can be made usable. When tes indications are not subject to unrelated variables, straight amplificatio is all that is required by the signal handling system.

b. In general, signal handling subsystems can be classified as one o the following.

(1) Impedance-magnitude type, which indicates only the magnitud of variations in the total coil impedance regardless of the pha or direction in which it occurs on the impedance plane (fig. 32

(2) Inductive reactance magnitude type, in which changes in induc reactance (ωL) are of interest without regard to changes in t resistive component of the total impedance. Usually, the cha in the inductive reactance of the coils are used to vary the resonant frequency of tuned circuits (fig. 33).

(3) Feedback-controlled type, in which the phase angle, or ratio the inductance to resistance of the test coil circuit, influences the feedback factors of self-excited oscillator circuits (fig. 34

(4) Impedance vector analysis type which indicates both the magni tude and phase angle of impedance variations (fig. 35).

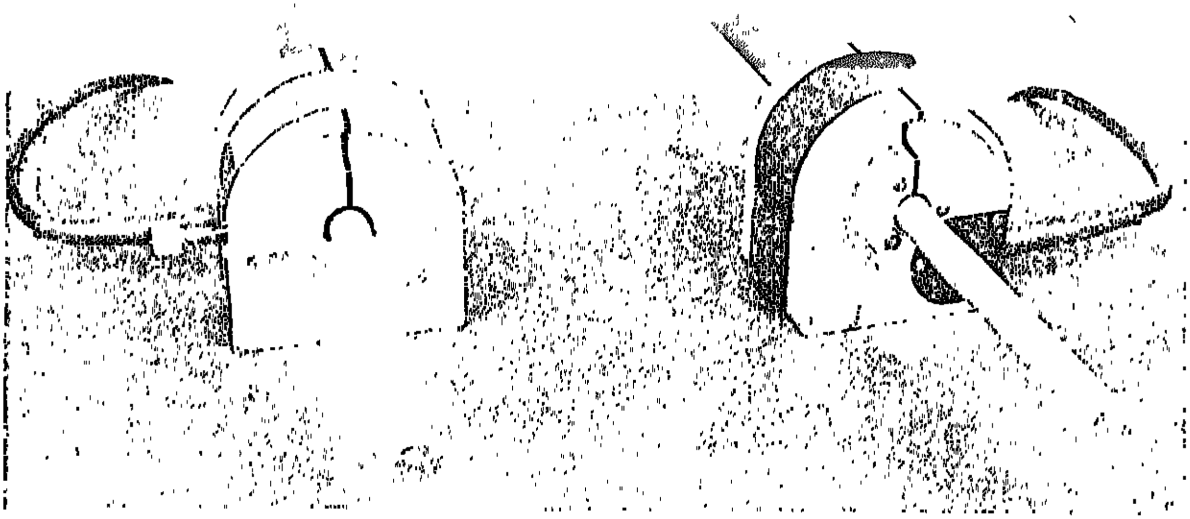


FIGURE 30. DIFFERENTIAL COIL ARRANGEMENT - EXTERNAL REFERENCE

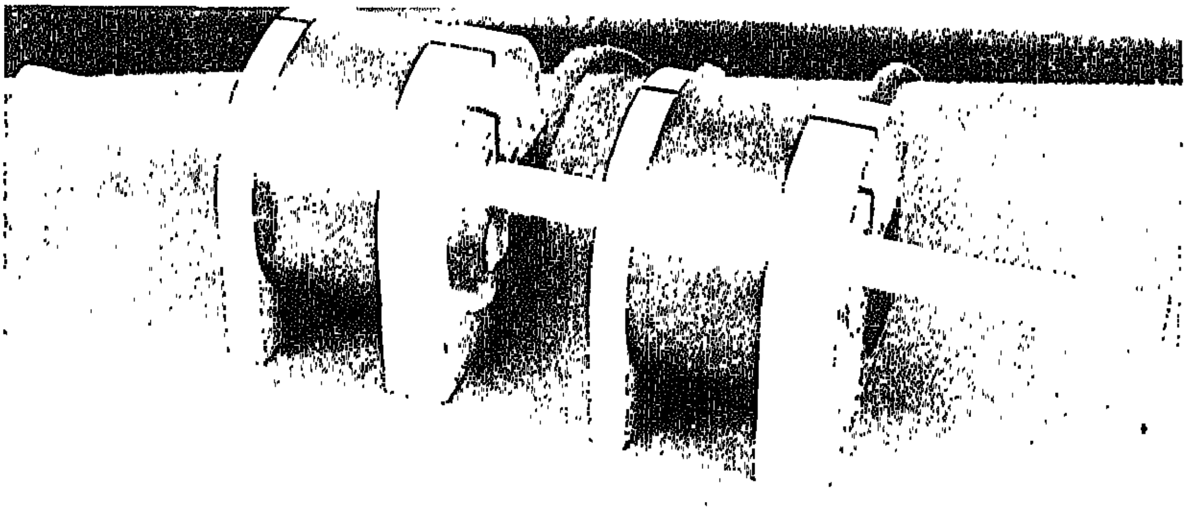


FIGURE 31. SELF COMPARISON DIFFERENTIAL COIL ARRANGEMENT

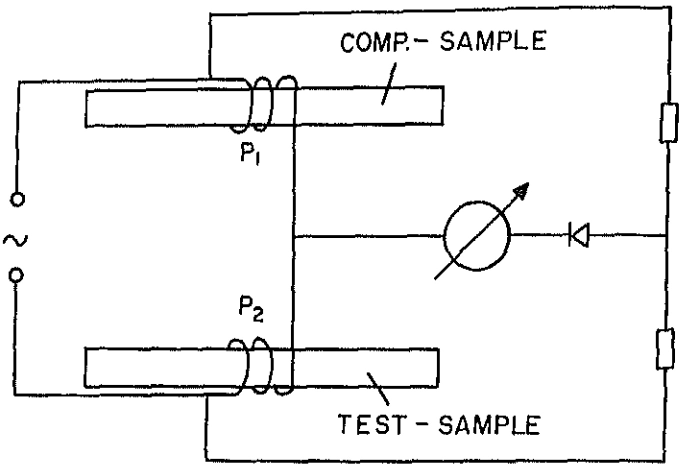


FIGURE 32. SIMPLIFIED DIAGRAM OF IMPEDANCE - MAGNITUDE TEST INSTRUMENT WITH BRIDGE CIRCUIT AND TWO PRIMARY COILS, USING COMPARISON STANDARD TEST SPECIMEN

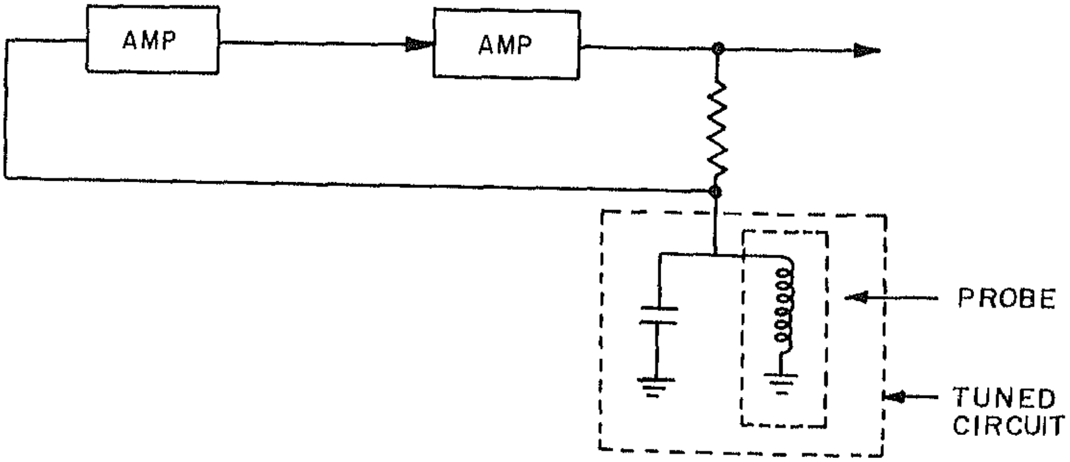


FIGURE 33. INDUCTIVE REACTANCE SIGNAL PROCESSING CIRCUI

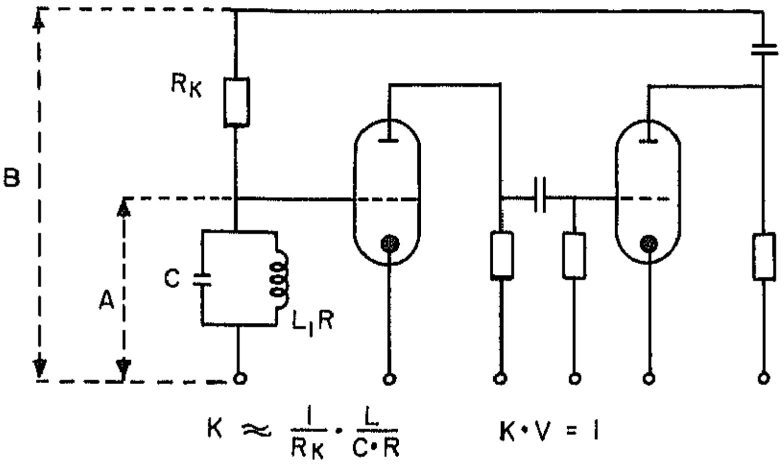


FIGURE 34. BASIC OSCILLATOR CIRCUIT USED IN FEEDBACK-CONTROLLED IMPEDANCE TEST SYSTEMS

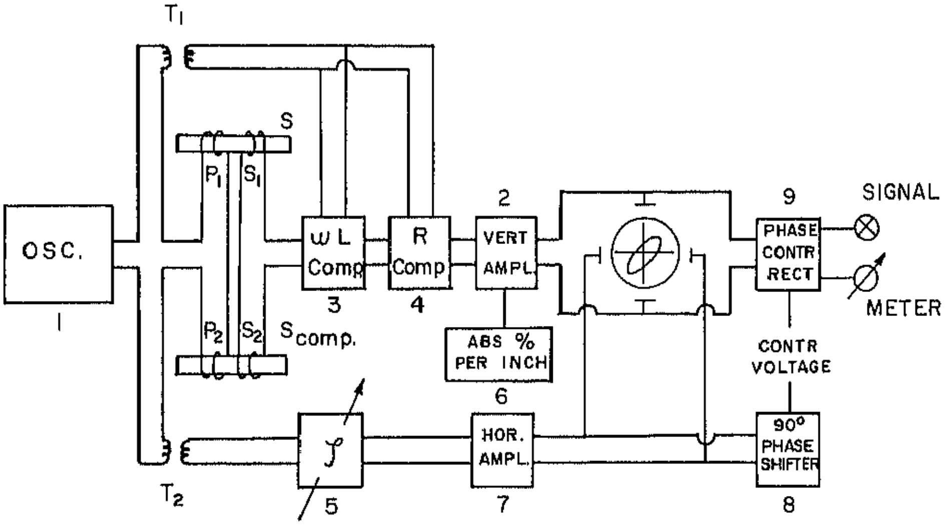


FIGURE 35. IMPEDANCE VECTOR ANALYSIS SIGNAL PROCESSING SYSTEM

In addition, all of these subsystem types may include circuits which su press the indications caused by undesired test object variables.

28. SIGNAL UTILIZATION (READOUT).

Many methods are used to present electromagnetic test indications to a observer or to automatic selection or control devices. The type of rea out subsystem to be used is based on the type and amount of informatio required from the test, the type and arrangement of the sensing elemen and the operational characteristics of the signal handling subsystem. Figure 36 shows one type of readout device. Some of the more commo methods are as follows:

a. Calibrated and uncalibrated meters

b. Direct numerical (digital) readout

c. Null meter with dial indicator

d. Oscilloscopes

  (1) Lissajous (ellipse)

  (2) Sine wave

  (3) Flying dot

  (4) A-scan

  (5) Hysteresis curve (B-H loop)

e. Alarms, lights, etc.

f. Defect marking systems (paint spray, dye marker, etc.)

g. Sorting gates

h. Automation and feedback (process control)

i. Strip chart and X-Y recorder.

Section III. TEST SYSTEM FACTORS

9. GENERAL.

ther important factors which must be considered in the choice or design are test frequency, coupling, and field strength.

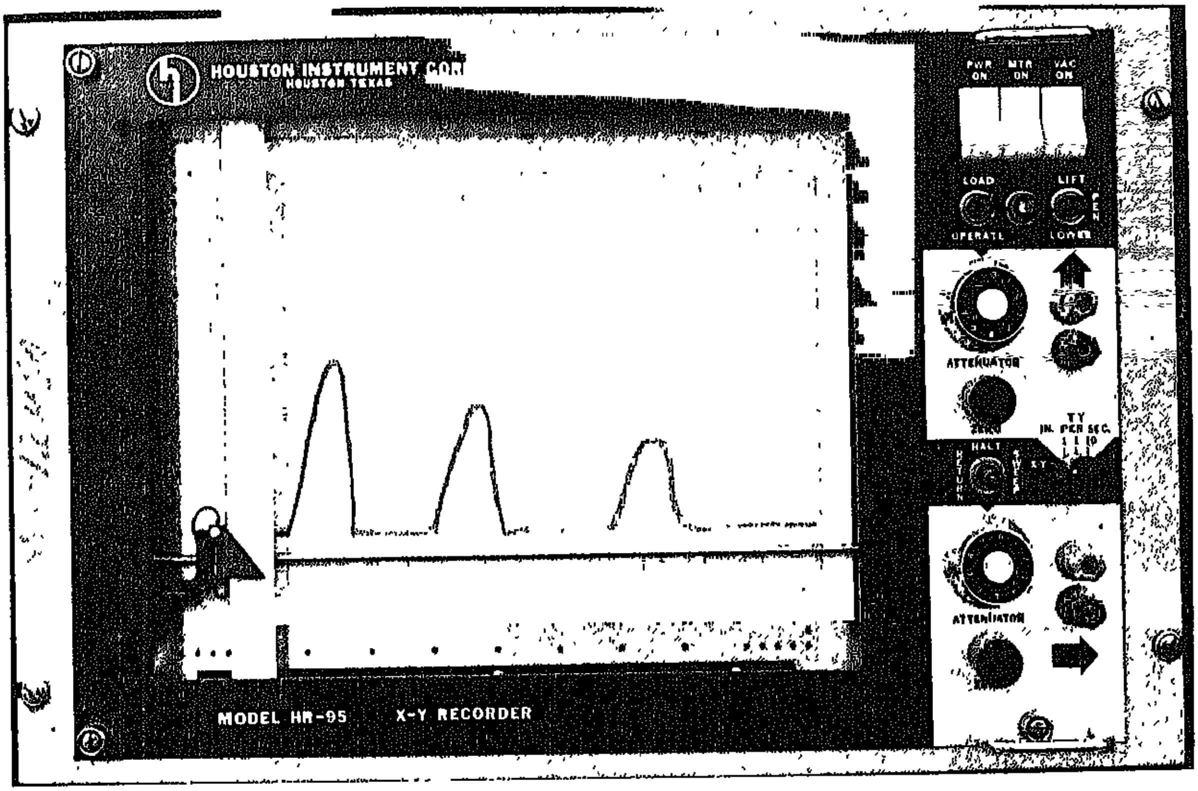


FIGURE 36. X-Y RECORDER READOUT

30. TEST FREQUENCY.

a. Since there is a wide range of frequencies available in modern electromagnetic test equipment, the question often arises as how to choose the proper frequency for a given test. Figure 37 shows the frequencies commonly used for different test problems. However, the frequency ranges shown do not always hold, since there are other considerations affecting the choice. Among the most important of these is the "skin effect" (effective depth of penetration). The effective depth of penetration is defined as the depth at which the electromagnetic field strength has dropped to 36.8 percent (1/e) of its value at the surface, and is expressed as

$$\delta = \frac{1}{\sqrt{\pi f \sigma \mu}}$$

where δ = effective depth of penetration

f = test frequency

σ = conductivity

μ = permeability

b. Figure 38 shows how frequency varies with depth of penetration for selected materials. It is obvious that in order to detect discontinuities that lie below the surface, the test frequency should be chosen so that the defects lie within the zone of effective depth of penetration. On the other hand, in making measurements on thin sections, the test frequency should be chosen so that the effective depth of penetration is less than (one half o one third) the thickness of the test object, otherwise errors in the measurement will arise due to variations in test object thickness. When probes are used as sensing elements, the frequency can be chosen to minimize lift-off errors caused by variations in probe-to-test object spacing.

c. When feed-through (encircling) coils are used as sensing elements, the characteristic frequency (f_c) of the test object is especially valuable in determining the proper test frequency (f) for a specific application. Complex impedance voltage and effective permeability curves for many materials have been worked out and can be found in the literature. The best f/f_c ratio for a given material can be taken from these curves and other theoretical and empirical data, and the characteristic frequency of a test object can be calculated from

$$f_c = \frac{1355}{\sigma D^2 \mu}$$

where f_c = characteristic frequency in cycles per second,

σ = electrical conductivity of test object in % IACS,

D = diameter of test object in inches, and

μ = magnetic permeability of the test object ($\mu = 1$ for non-magnetic materials)

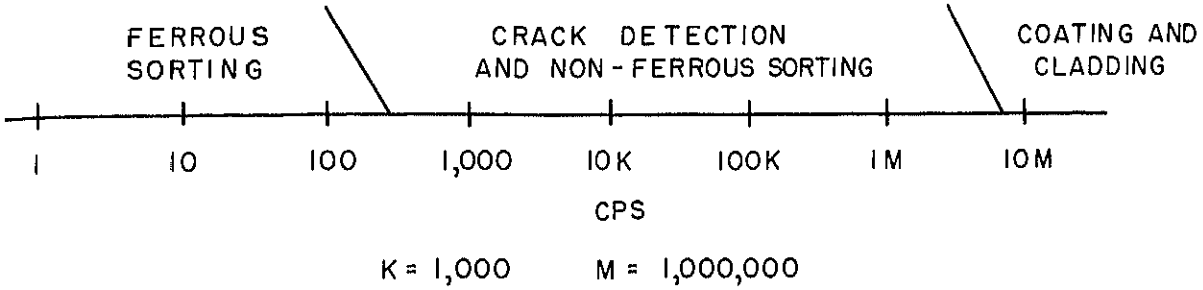


FIGURE 37. FREQUENCIES USED FOR VARIOUS TEST PROBLEMS

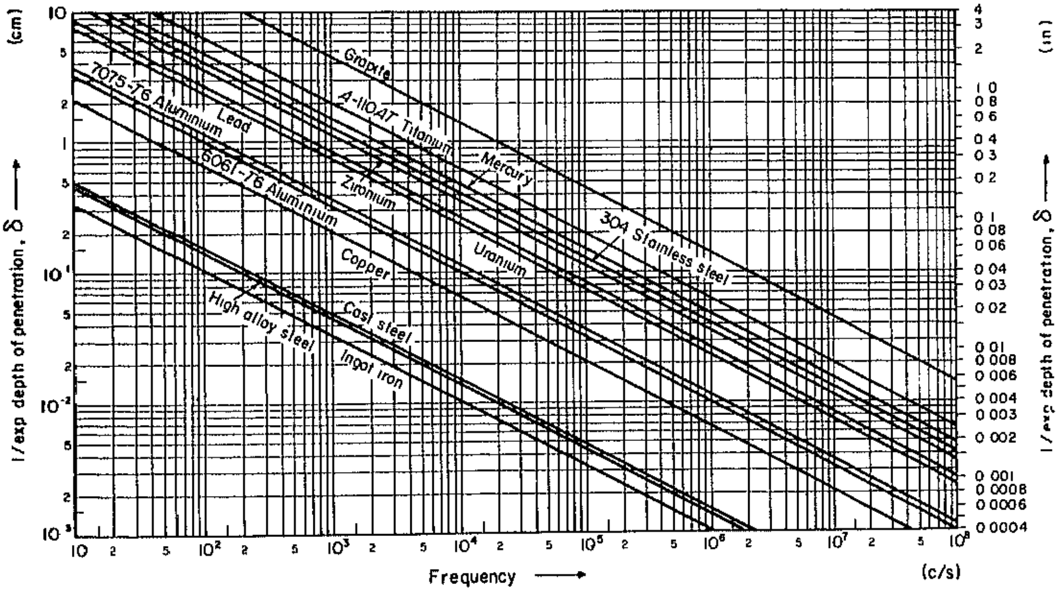


FIGURE 38. RELATIONSHIP BETWEEN DEPTH OF PENETRATION IN VARIOUS METALS AND TEST FREQUENCY (PLANE CASE)

Multiplying the f/f_c ratio that has been selected, by the calculated f_c, yields the proper test frequency to be used for a given problem.

d. From experience, certain f/f_c ratios are known to be best for certain applications. In tubing inspection, where conductivity variations are of interest, an f/f_c ratio of 6.25 is a good choice. When general tubing inspection for defects is the application, a ratio of f/f_c of 15 will give good results. To evaluate diameter variations in tubing, a good f/f_c ratio is 100. The frequencies found to be most suitable in particular applications are by no means exact quantities. Generally, there is a range of suitable frequencies centered around the optimum frequency that will give satisfactory results. In practice, test systems are provided with circuits that allow any frequencies to be chosen over a wide range. Other system of a specialized nature, come with a single fixed frequency which is an optimum for a particular type of application.

31. COUPLING

a. Another important test system factor is coupling. In systems wher encircling coils are used, coupling is known as the fill factor (N). In systems where probe coils are used, it is known as lift-off.

b. In systems using encircling coils, the fill factor is expressed as

$$N = \frac{D^2}{d^2}$$

where N = fill factor,
D = diameter of the test object, and
d = diameter of the coil.

The complex voltage and impedance planes upon which much of test system design is based, include the fill factor quantity. This is expected, since a variation in fill factor can be viewed (assuming constant coil diameter) as a variation in the diameter of the test object. For best sensitivity, the fill factor should be as high as possible; i.e., the test coil should fit the test object being examined as close as possible. Figure 39 shows an example of good and poor fill-factor practice.

c. In test systems where probe coils are used as sensing devices, oupling is referred to as lift-off. Lift-off is manifested by signal variaions in the readout circuit caused by changes in impedance in the probe oil due either to rocking of the probe, or to poor test object surface onditions. It must be pointed out that lift-off is not always undesirable. ctually, a whole area of test system design is based on the knowledge hat the coil impedance will vary as the spacing between the test object nd probe coil varies. Systems designed to measure the thickness of nonnetallic coatings on a metallic base use this principle.

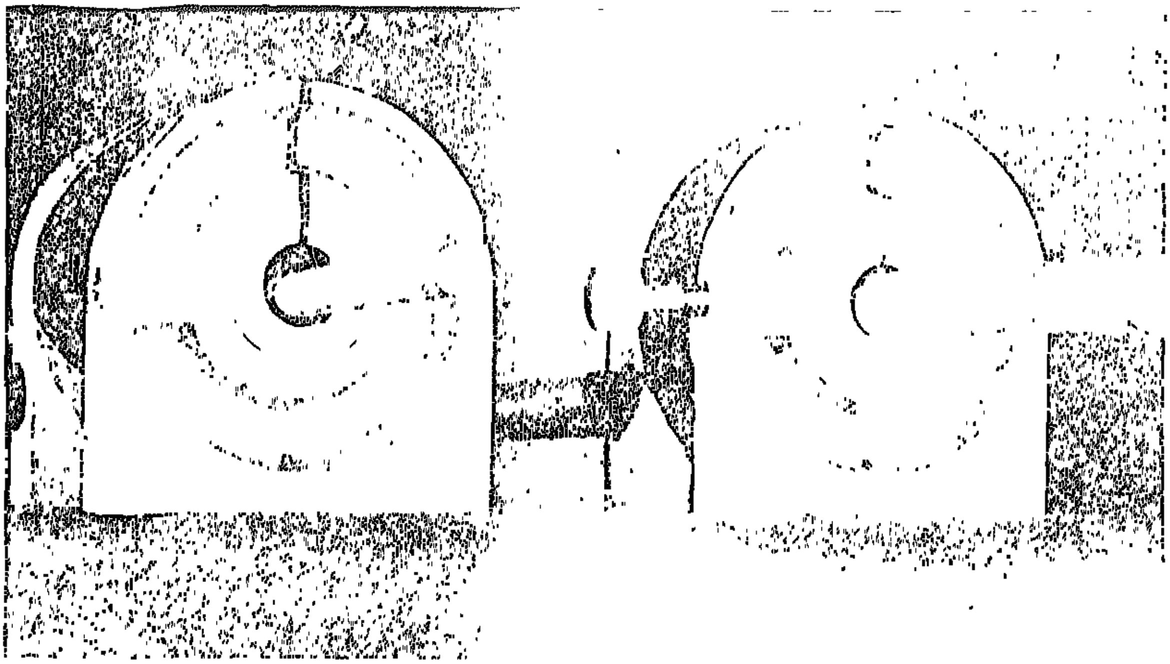


FIGURE 39. ILLUSTRATION OF GOOD AND POOR FILL FACTOR

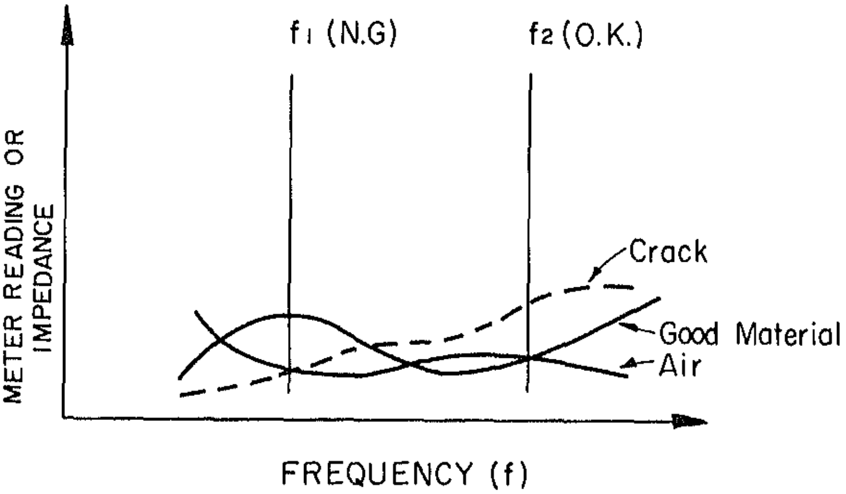


FIGURE 40. LIFT-OFF COMPENSATION AS A FUNCTION OF FREQUENCY

d. In test systems where lift-off effect is undesirable, two methods are generally used to compensate for changes caused by variations in probe-to-test object spacing. They are:

(1) the variable frequency method, in which the excitation frequency driving the probe coil is adjusted to a value that gives the same probe impedance in air, as on good material, but a different probe impedance over a variable of interest (crack, seam, etc); however, this must be done after checking the effect of the frequency change on other factors such as depth of penetration requirements (see fig. 40), and

(2) mechanical fixture method, in which the probe coil is held a fixed distance from the test object by a suitable mechanical arrangement.

32. FIELD STRENGTH

a. In connection with magnetoinductive test systems, when ferromagnetic test objects are to be examined, there is the special problem of selecting the proper field strength. In chapter 2, the relationships between the magnetic characteristics and the physical properties of test objects were pointed out. In sorting applications where the test objects are ferromagnetic, the test system will provide information based on both permeability and conductivity variations. If the sorting is based on permeability variations, special considerations are necessary. Since permeability is not a constant, but depends on field strength, it is entirely possible that he wrong field strength might make a seperation based on permeability mpossible. Referring back to figure 11, notice that at field strength H_1, e normal induction curves of test object A and test object B cross each ther. At field strength H_2, the induction curves are separated. This hows that if field strength H_1 were used to sort test objects A and B, the est coils would see no apparent magnetic difference in the two test objects, nd the output indication would be the same for both pieces. On the other hand, if field strength H_2 were used, the test objects would show a difference in their magnetic properties, resulting in a change in output indication when test objects A and B are alternately placed in the coil.

b. In magnetoinductive test systems for sorting ferromagnetic speciens, where the magnetic permeability variation contains the information ired, the following points should be kept in mind.

(1) The magnetizing force (H) the test object is subjected to, is determined by the level of coil current in the secondary.

2) The permeability (μ) of the test object at the magnetizing force level established by the current in the primary, determines the flux density (B).

) The value of flux density in the test object determines the level of voltage induced in the secondary coil.

(4) The value of induced secondary voltage determines the indications in the signal utilization subsystem.

This all adds up to the fact that the readout is directly related to the applied magnetizing force.

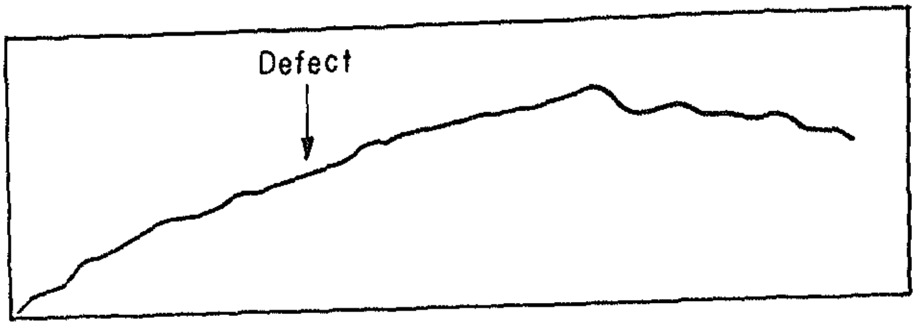
c. In discussing operating field strengths for magnetoinductive system design, several other factors should be mentioned which must be considered in selecting the proper field strength levels. When the operating field strength in a magnetoinductive system is increased, the depth of penetration of the magnetic field into the test object is decreased due to eddy current shielding and permeability gradients. Hence, when good penetration is required, a low value of magnetizing force should be selected. However, when short stubby test objects are placed in encircling coils, there may be depolarization effects caused by the magnetic poles that are formed at the test object's ends. In such cases, it is often necessary to operate at high values of field strength to overcome this apparent self-demagnetization of the test part.

Section IV. THE SIGNAL-TO-NOISE RATIO

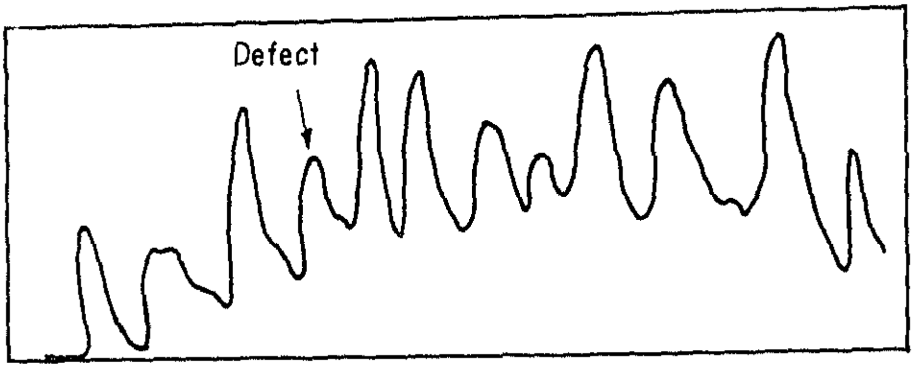
33. GENERAL.

a. The concept of the signal-to-noise ratio is important in eddy current and magnetoinductive test systems. The signal-to-noise ratio will determine the feasibility of solving a given problem with a particular test system. "Signal" is here defined as the indication in the signal utilization (readout) subsystem produced by the relevant variable or discontinuity of interest. "Noise" is defined as that indication in the signal utilization (readout) subsystem produced by irrelevant background conditions. Consider the situation where an eddy current test system, using feed-through coils, is examining copper tubing for cracks. The diameter of the copper tubing varies (within production tolerances) throughout its length. The indications caused by a crack in the tube are the "signals", while the indications caused by diameter variations are the "noise" (fig. 41).

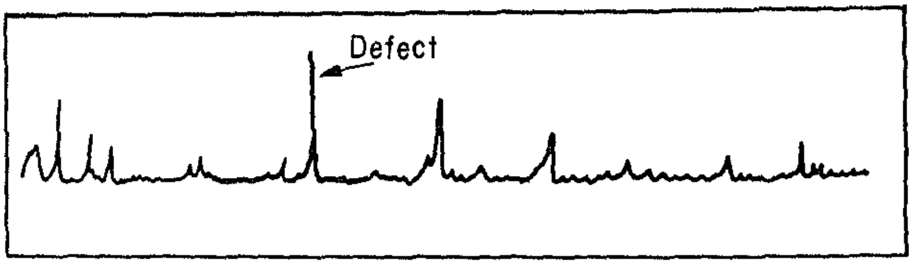
b. In a magnetoinductive test system using a probe coil to evaluate heat treatment effects, permeability variations due to residual stresses are also present. The indications caused by heat treatment effects are the "signal", while indications caused by areas of residual stress are classified as "noise". In most electromagnetic test system applications, a minimum acceptable signal-to-noise ratio of 3 to 1 is required for reliable inspection. This means that the "signal" indication in the readout circuit should be at least three times larger than indications caused by "noise". When a test system does not produce at least a 3 to 1 signal-to-noise ratio, it is not advisable to proceed with the test. This does not mean that the problem cannot be resolved, however, for there are special techniques available which can be used to improve the signal-to-noise ratio.



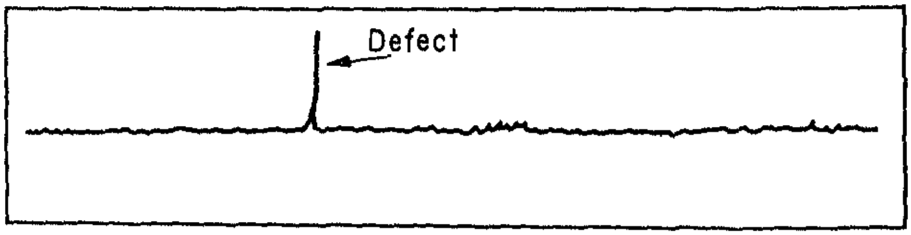
(a) VERY LOW FREQUENCIES ONLY



(b) LOW AND VERY LOW FREQUENCIES



(c) INTERMEDIATE FREQUENCIES



(d) VERY HIGH FREQUENCIES

FIGURE 41. APPEARANCE OF THE SAME OUTPUT SIGNAL WHEN SUBJECTED TO VARIOUS DEGREES OF FILTERING

34. IMPROVING THE SIGNAL-TO-NOISE RATIO

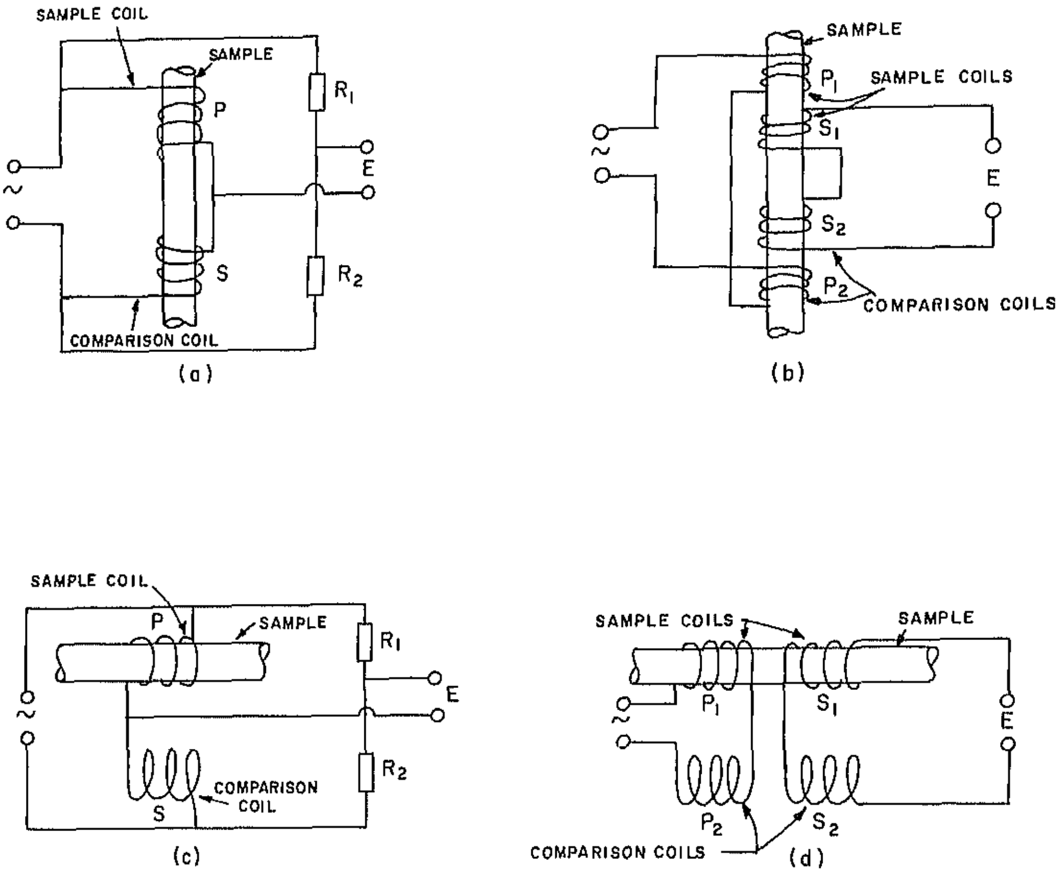
a. When it becomes apparent that a test system is not capable of solving a given problem due to a poor signal-to-noise ratio, there are certain modifications that can be made on the test system which may result in an improved signal-to-noise ratio. It should be noted that increasing the sensitivity of the test system will not help, since increasing the amplification of the signal also increases the amplification of the noise which does not change the ratio.

b. Several areas of modification have already been presented. The factors introduced as test frequency, coupling, and field strength, which are used in the initial design of a test system, can also be altered in a special way to improve the signal-to-noise ratio of the system. Actually, those points mentioned for consideration in the initial system design are built-in factors to improve the signal-to-noise ratio. (See section III of this chapter.) It must first be determined if a change in test frequency will suppress the noise indications while leaving the desired signal information intact, and secondly, the proper coil design must be used.

c. In systems where encircling coils are used to inspect test objects being fed through them, proper coil configuration can do much to suppress noise. The differential or self-comparison configurations (fig. 42a and b) are often used in crack detection test systems, since the crack depth normally varies from point to point along the test object. Noise from one test object to another has no effect with these coil configurations since their influence on the effective permeability of each coil section is equal but opposite and hence, cancels out. In addition, slowly varying physical properties within a test object are also suppressed when the two self-comparison coil elements are located close to each other.

d. Another very sensitive configuration is the absolute, or standard-of-comparison type. Figure 42 c and d shows two variations of this technique. This method is much the same as the differential configuration method with the exception that an external comparison standard is used as a compensating factor instead of using the test object itself. It has the advantage of allowing a choice as to the type and degree of noise suppression employed in the system. It is only necessary to select a standard with the appropriate variable. This arrangement is more suited to overall analysis work where it is desirable to know if the physical properties (such as conductivity, permeability, etc.) of the test object vary from those of the standard of comparison.

e. In both of the foregoing methods, when the sample and the comparison coils both contain material of identical physical properties, the voltage measured across the coils will be the same. If on the other hand, the material properties are different, there will also be a difference in the measured voltage across the coils.



a. Self comparison arrangement of two primary coils

b. Self comparison arrangement of two primary and two secondary coils

c. Bridge circuit of two primary coils

d. Bridge circuit with two primary and two secondary coils

FIGURE 42. ARRANGEMENTS OF TEST COILS FOR FEED-THROUGH TESTS

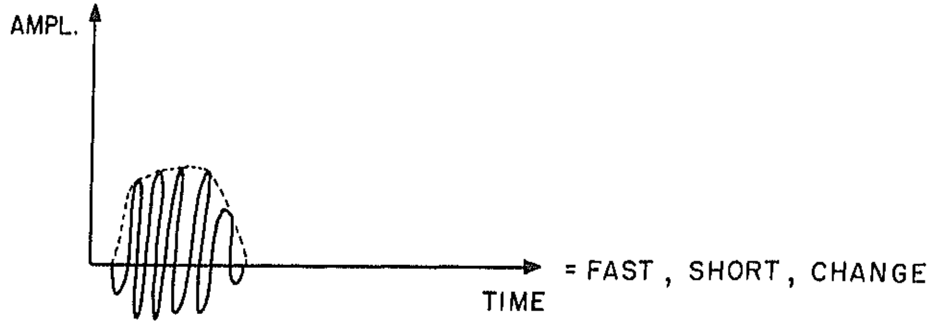
5. FREQUENCY, PHASE, AND AMPLITUDE

a. General. In paragraph 27 on signal handling subsystems, it was pointed out that the three significant properties of a test coil signal are frequency, phase, and amplitude. In practice the signal from the test coil contains all three properties. However, the information of interest is usually obscured in this complex signal, and it becomes necessary to weed out the desired data. In most cases, this information has a characteristic behavior. It may have certain frequency properties, or it may cause a phase shift in the signal. More often than not, it is a combination of frequency, phase, and amplitude. By skillful handling of the three basic properties, a test system can perform even when faced with a large number noise variables. Some of the more common techniques shall now be introduced.

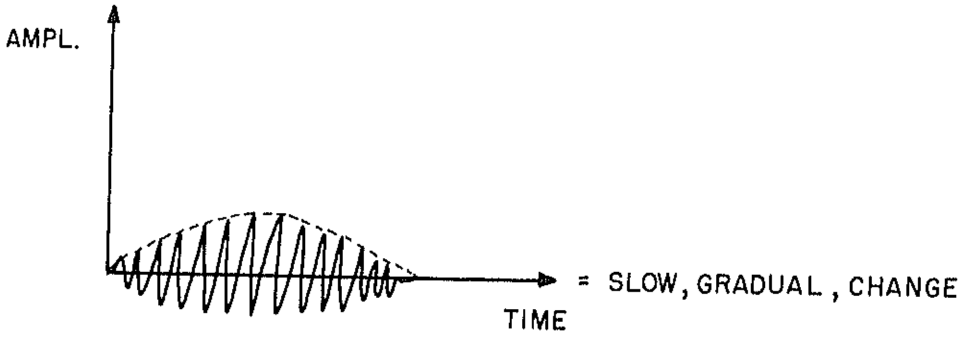
b. Frequency.

(1) Since the response of the test coil to the test object variables occurs over discrete intervals of time, it must be understood that the test frequency can be viewed as a modulated carrier, where the modulation is supplied by the variation of coil impedance with time. It is well known that signals which vary with time contain a frequency spectrum which is dependent upon the time rate of change of the signal. Since the time rate of change of the coil impedance is dependent on the test method and the test object properties, several interesting relationships become apparent (fig. 43).

(2) One technique which should be mentioned is frequency discrimination (electronic filtering). This operation is usually performed by the signal-handling subsystem, and is nothing more than providing the system with a frequency selective capability. This is generally accomplished by means of an electronic circuit whose output is frequency dependent. In the case of inspection of tubing for defects, where the tubing is fed through encircling test coils, there are at least two different types of time varying signals. Because of their relatively short length, crack-like defects in a tube pass in and out of the test coils in a very short time period. On the other hand, variables such as diameter, grain size, or conductivity tend to occur over longer lengths of the tube and are usually more gradual changes. This means that at some given section on the tube, the defect which appears as a fast, short change in properties, is superimposed on slow, gradual changes which are normal for the tubing. This represents a classic example of the signal-to-noise concept. The fast, short changes caused by defects are the signals of interest. The slow, gradual changes caused by such variables as diameter, are unwanted background noise. If a recorder were used to monitor the system output, the results would appear as shown in figure 44a. The signal-to-noise ratio here is only 2/1; this would not be an

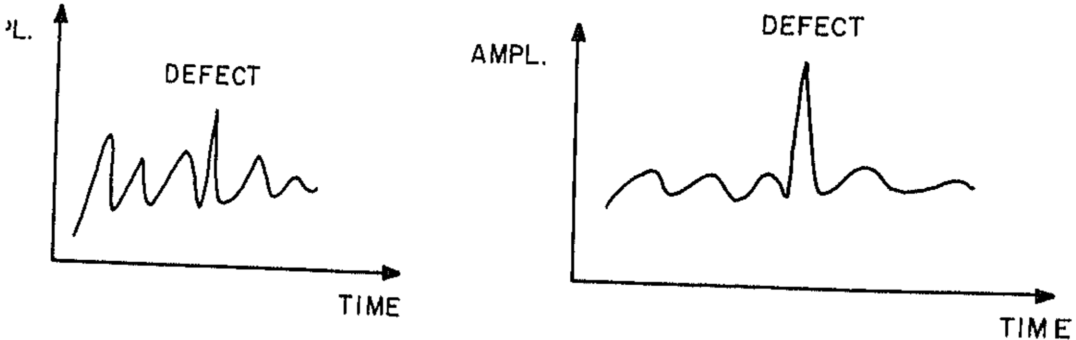


DEFECT IN TUBE



DIAMETER VARIATION IN TUBE

FIGURE 43. TIME-RATE OF CHANGE RELATIONSHIPS



a. Without

b. With

GURE 44. EFFECT OF DIFFERENTIATION ON READOUT SIGNAL acceptable ratio for testing since it would be possible for the background noise to mask the defect signal. To overcome this problem, a circuit which is frequency selective can be incorporated into the signal handling subsystem.

(a) If the circuit is so designed that its output response is large for high frequencies (fast, short changes such as from a defect), and small for low frequencies (short, gradual changes as from diameter variations), the process is known as differentiation or high-pass filtering. The simplest type of differentiating circuit is the resistance-capacitance (R-C) type where the R-C time constant is made small compared to the time duration of the slowly changing noise variations. If the recorder now monitors the system output after incorporating the filter circuit, the system output would appear as shown in figure 44b.

(b) Another important application of electronic filtering arises in the testing of ferromagnetic test objects. When a magnetoinductive test system is used to sort ferromagnetic test objects, it is generally true that a great deal of distortion due to harmonics of the fundamental test frequency will be present in the system output. When it becomes necessary to deemphasize this harmonic distortion, electronic integration circuits can be incorporated into the signal handling subsystem. Electronic integration is essentially the inverse operation of electronic differentiation. It is frequency selective, and so designed that its output response is large for low frequencies (slow, gradual changes with respect to time), and small for high frequencies (fast, short changes with respect to time). Figure 45 shows the output of a magnetoinductive system as it appears before and after electronic integration. The simplest type of integration circuit is also the resistance-capacitance (R-C) type (see the preceding paragraph for the differentiating type circuit), where the R-C time constant is made large compared to the time duration of the rapidly changing noise variations. A point to remember is that in some system applications, the harmonic distortion might provide the information required for sorting. In such cases, filtering would not be desirable.

c. Phase. Another important circuit technique is known as phase discrimination. In both magnetoinductive and eddy current test system applications, it is often found that variables encountered in test objects are manifested in the system output by changes in phase as well as amplitude. Many test systems are provided with phase-selective circuitry, but in general, there are two types of major importance.

(1) The first of these types is generally referred to as the ellipse or Lissajous readout. With this type of system, it is possible

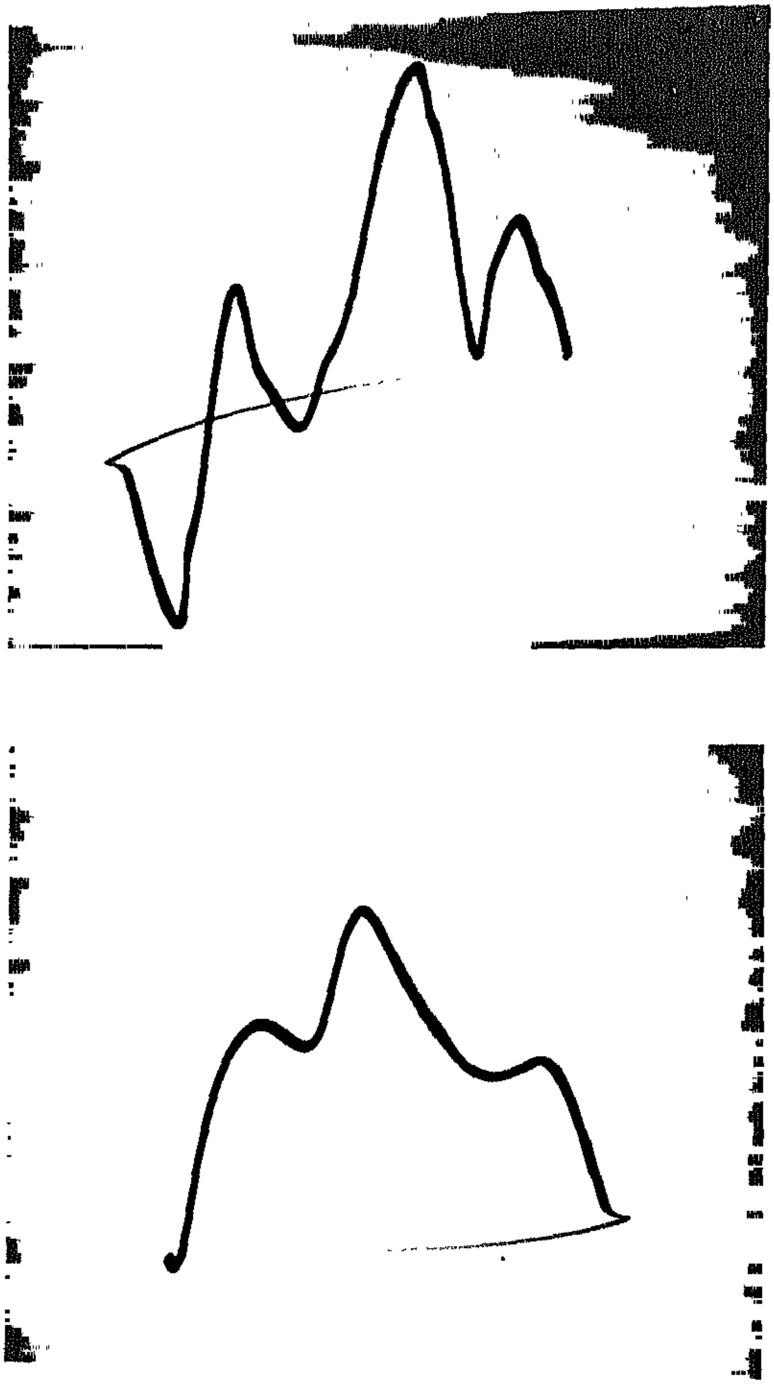
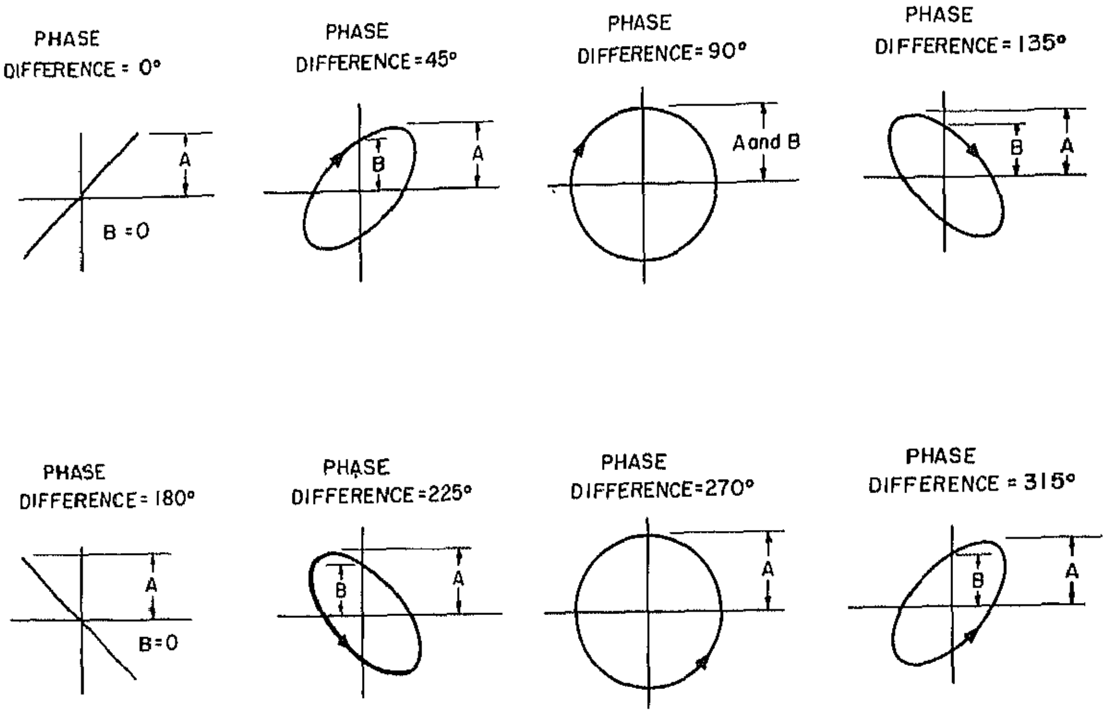


FIGURE 45. OUTPUT INDICATIONS BEFORE AND AFTER INTEGRATION

to separate indications caused by cracks from those indications caused by diameter variations. This type of system is very useful in inspecting rod, tube, and wire for surface and subsurface cracks. Since the coil impedance vectors for diameter and cracks are perpendicular to each other, the ellipse on the screen will show two distinct types of behavior. The opening of the ellipse as measured on the vertical axis is proportional to the crack indication, while the orientation of the ellipse is proportional to the diameter variation (see fig. 46 for phase-amplitude relationship). Figure 47 shows the ellipse pattern for situations that arise in testing rods for surface and subsurface defects. Figure 47a shows the pattern as it appears when the rod diameter is the same as the comparison standard and no crack is present. This condition is usually called the balance condition. Figure 47b shows the ellipse pattern when a crack is present in the rod and when the diameter has not varied from the standard dimension. Note that the crack has caused the ellipse to open. The amount that the ellipse opens (as measured on the vertical axis) is proportional to the crack dimensions and location. Figure 47c shows the ellipse pattern for a change in rod diameter with no crack present. Figure 47d shows the ellipse pattern when a diameter variation and a crack appear at the same point on the rod. The crack properties are still measured on the Y-axis independent of the orientation of the ellipse. This type of test system is well suited for measuring diameter variations as well. It can also be used to sort various alloys in finished and semifinished form.

(2) The other important phase discriminating type of system uses a linear time base oscilloscope readout rather than a Lissajous type. Figure 48 shows a block diagram of a typical magneto-inductive linear time-base test system. This type of system is not as elaborate as the ellipse system; it provides one cycle of the wave train for viewing, by driving the horizontal deflection plates of the oscilloscope with a saw-toothed voltage of predetermined duration. The time base can be shifted in phase to any desired reference. The vectors for diameter and permeability variations are at right angles to the conductivity vector. Then, if the phase of the time-base voltage used to synchronize the horizontal sweep of the oscilloscope is chosen to correspond with the phase direction caused by permeability or diameter variations, a change in these two quantities will have no effect on a measurement made at the 180 degree position of the sine wave presentation. However, if a change in conductivity occurs, the measurement made at the 180 degree reference point will vary. Figure 49 shows the output traces as they would appear for conductivity variations in the test object. This method is sometimes known as the slit technique since the amplitude of the trace is read at the point where it passes through a slit placed over the cathode ray tube (CRT) screen.


PHASE DIFFERENCE = 0°

PHASE DIFFERENCE = 45°

PHASE DIFFERENCE = 90°

PHASE DIFFERENCE = 135°

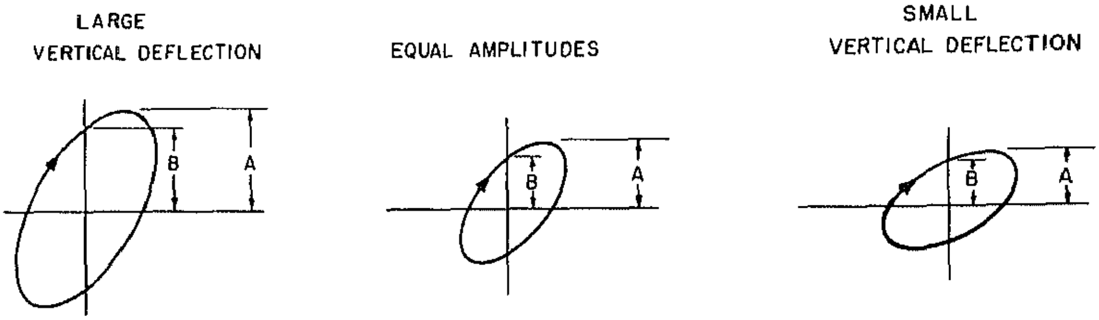
PHASE DIFFERENCE = 180°

PHASE DIFFERENCE = 225°

PHASE DIFFERENCE = 270°

PHASE DIFFERENCE = 315°

EQUAL AMPLITUDES AND VARYING PHASE DIFFERENCES


LARGE VERTICAL DEFLECTION

EQUAL AMPLITUDES

SMALL VERTICAL DEFLECTION

CONSTANT PHASE DIFFERENCE OF 45° BUT VARYING AMPLITUDE ON VERTICAL DEFLECTION

FIGURE 46. TYPICAL CRT PATTERNS WHEN SINUSOIDAL VOLTAGES OF THE SAME FREQUENCY BUT DIFFERING IN PHASE AND AMPLITUDE ARE APPLIED TO THE HORIZONTAL AND VERTICAL DEFLECTORS

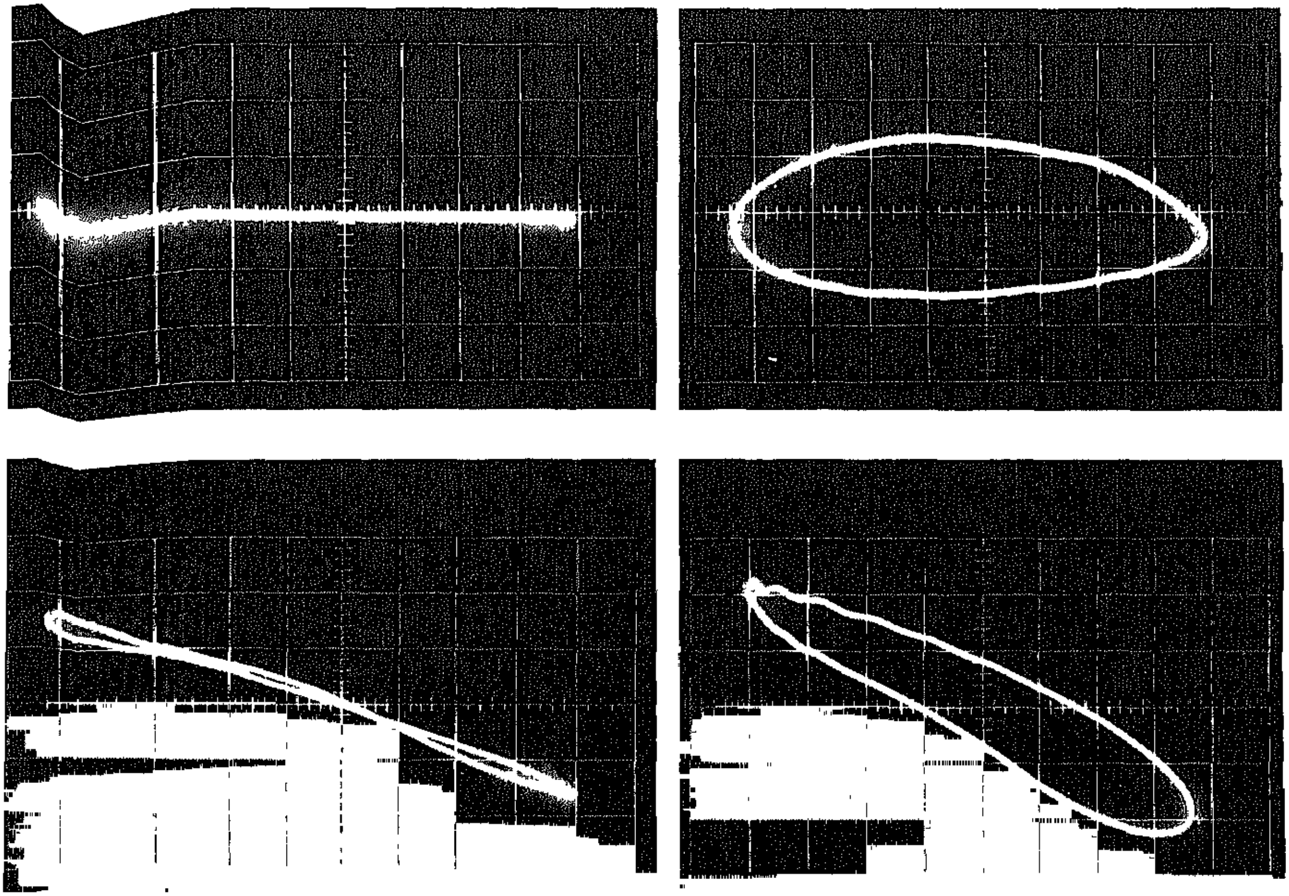


FIGURE 47. ELLIPSE TEST SYSTEM OUTPUTS

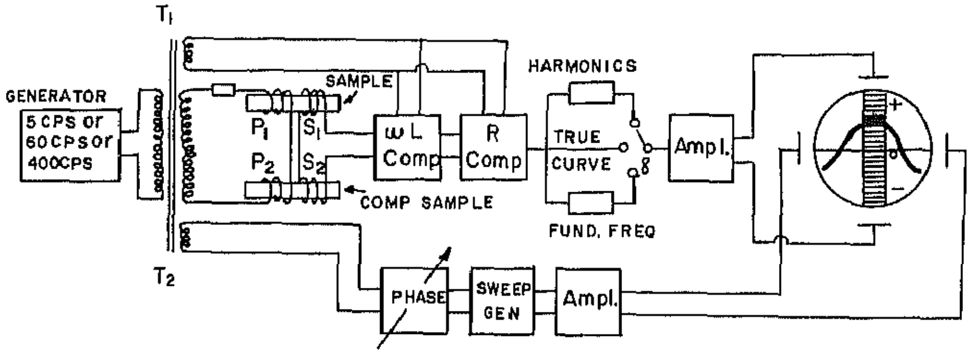
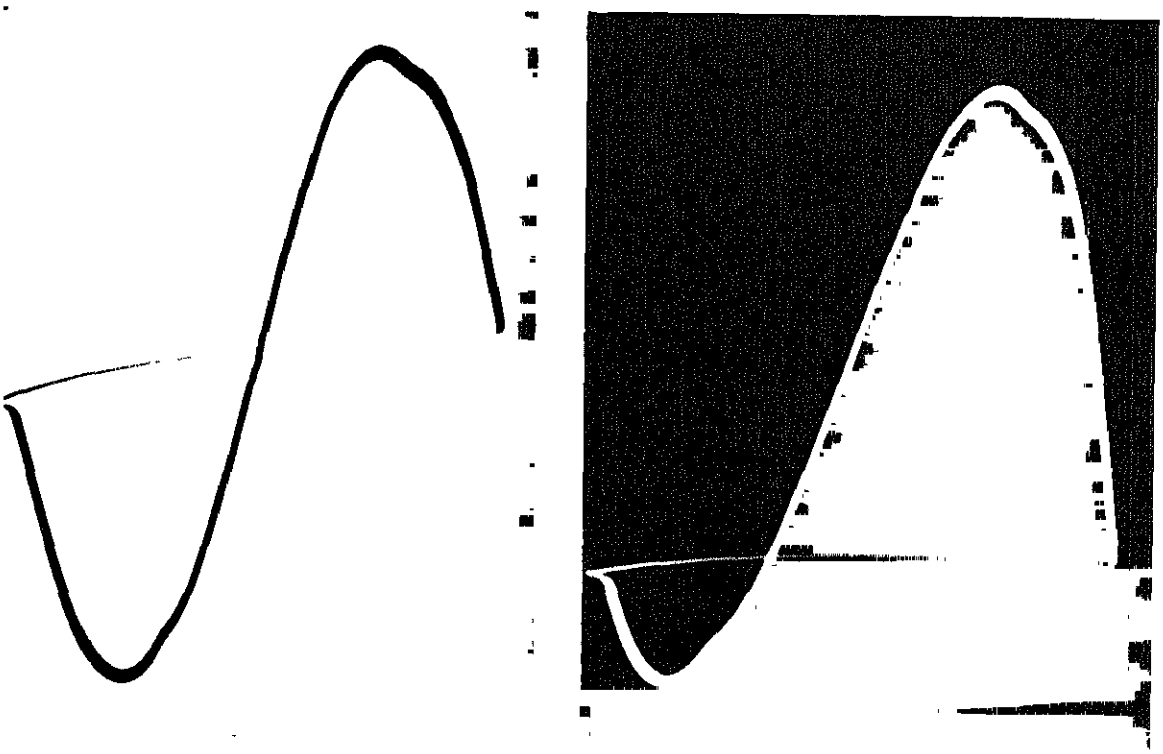


FIGURE 48. WIRING DIAGRAM OF LINEAR TIME - BASE TEST SYSTEM



GURE 49. OUTPUT TRACES FOR CONDUCTIVITY VARIATION IN TEST OBJECT

ere are other types of test systems where phase discrimination is em- yed. In some of these systems, the output is read from a meter, the se discrimination being performed in the signal handling subsystem by a se-controlled rectifier circuit. This circuit indicates only those com- nents of the test coil voltage which have the same phase direction as control voltage, whose phase is adjustable.

d. Amplitude. When a situation arises in a given test, where noise riables are not present, or do not obscure the magnitude of test object anges of interest, amplitude measurements made on the complex signal e normally sufficient for a successful test. Magnetoinductive and eddy rrent test systems which display the peak amplitude of the complex test il signal can be used for inspection of test objects. Therefore, special- ed test systems which present specific information on frequency-phase- plitude relationships can also be used. The straight amplitude case is re often found when nonferromagnetic test objects are to be examined. en ferromagnetic test objects are to be investigated, the additional ise caused by permeability variations and harmonic distortion in the mplex waveform usually requires some kind of signal-to-noise improve- ent technique, i.e., frequency, phase, or amplitude discrimination, hough this is not a strict rule. Figure 50 shows a typical waveform where re is a simple amplitude change for variations in test object properties.

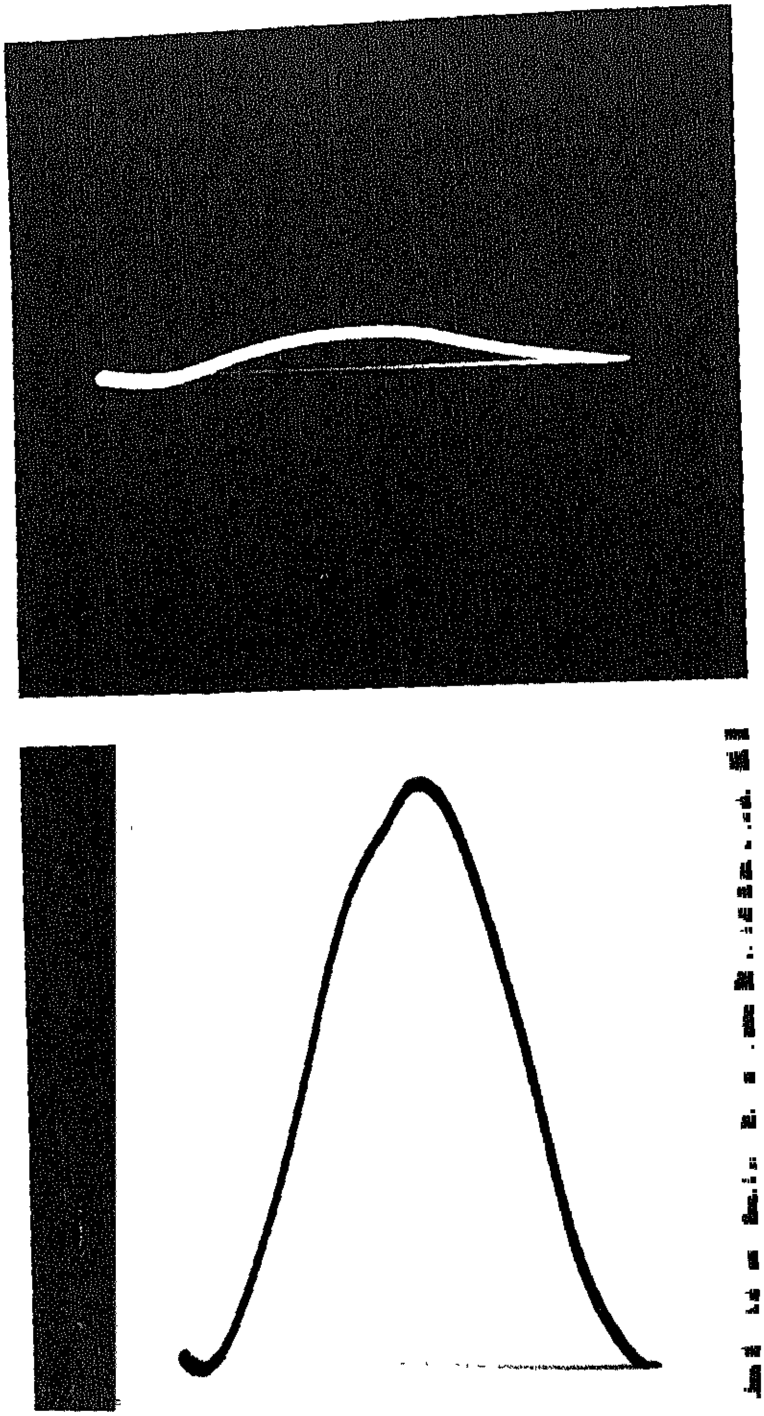
ction V. APPLICATION OF TEST SYSTEM DESIGN CONSIDERATIONS

. GENERAL

a. The theory behind electromagnetic test system design is very com- ex and only a limited coverage of this subject has been presented in this apter. Actually, the design, choice, and application of test systems is ore of an art than a science since in many cases, the individual involved not aware of problems caused by certain variables until testing has tually begun. Further, it is very difficult, if not impossible, to predict hat conditions are present in the test object and how they will influence st system response.

b. Many types of test systems are available. Although most test sys- ms are basically impedance bridges of one type or another, they come a variety of sizes, shapes, and designs. Some systems are used only r ferromagnetic materials, others for nonferromagnetic materials. me systems use probe coils, others encircling coils, while still others re designed for use on a variety of materials and use both probe and ncircling coils.

c. The question arises as to how the engineer or inspector chooses e proper test equipment. Perhaps the clearest way to show the process volved is to present and then solve a typical test problem. The solution resented, however, is not necessarily the only solution to the problem;



IGURE 50. OUTPUT INDICATION SHOWING AMPLITUDE DIFFERENCES

there are probably several other types of systems that would provide an effective examination of the test object.

37. PROBLEM - EXAMINATION OF GUN BARRELS

Several 20 mm gun barrels ruptured during firing tests. Metallurgical examination showed that the barrels, which were made from a molybdenum-chromium-vanadium steel, had been improperly heat treated. In the manufacture of the gun barrels, the heat treatment schedule called for a rapid water quench to produce a martensitic structure. If the quench rate were too slow, the structure would be comprised of ferrite, bainite and some martensite. This latter structure could cause the barrels to rupture when the gun was fired. It would not have been practical to scrap the large number of barrels that had been manufactured. What was needed was a fast, economical test method which would sort the good barrels from those which had been improperly heat treated. An electromagnetic test method successfully solved the problem.

38. SOLUTION

a. In applying test system design principles, the first important fact determined was that the barrels were ferromagnetic. It was reasoned that in a ferromagnetic material the magnetic and electrical properties would vary with the different heat treatment processes and, therefore, different heat treatments of the same material would be detectable by electromagnetic tests. Since the effects of heat treatment are usually the same throughout a material, they would not behave like localized discontinuities such as cracks or seams. This was important since it ruled out the necessity of scanning the entire length of the barrel. The effect of heat treatment, therefore, should have been detectable at any point on the barrel.

b. The next step involved obtaining a properly quenched barrel that was a 100 percent martensitic microstructure. This was determined by metallographic analysis. This barrel was then used as the "standard of comparison" in a comparator type test system.

c. Because of the shape of the gun barrel, encircling coils were used. Test frequency was in the order of 60 cps or less, since the material was ferromagnetic. Experience in similar sorting problems indicated a field strength of 25 to 75 oersteds. (Normally, the method of selecting field strength is to obtain normal induction curves from specimens representing both heat treatment conditions. When normal induction curves are not available, a series of trial and error tests are conducted to detect differences between specimens by varying field strength.) The signal handling system used was capable of straight amplification and it was assumed that undesired variables did not mask the heat treatment variation in the gun barrels. The readout for this particular case was either a meter or an oscilloscope. A block diagram of such a system is shown in figure 51. Using this test system, successful 100 percent inspection sorting of the gun barrels was satisfactorily accomplished.

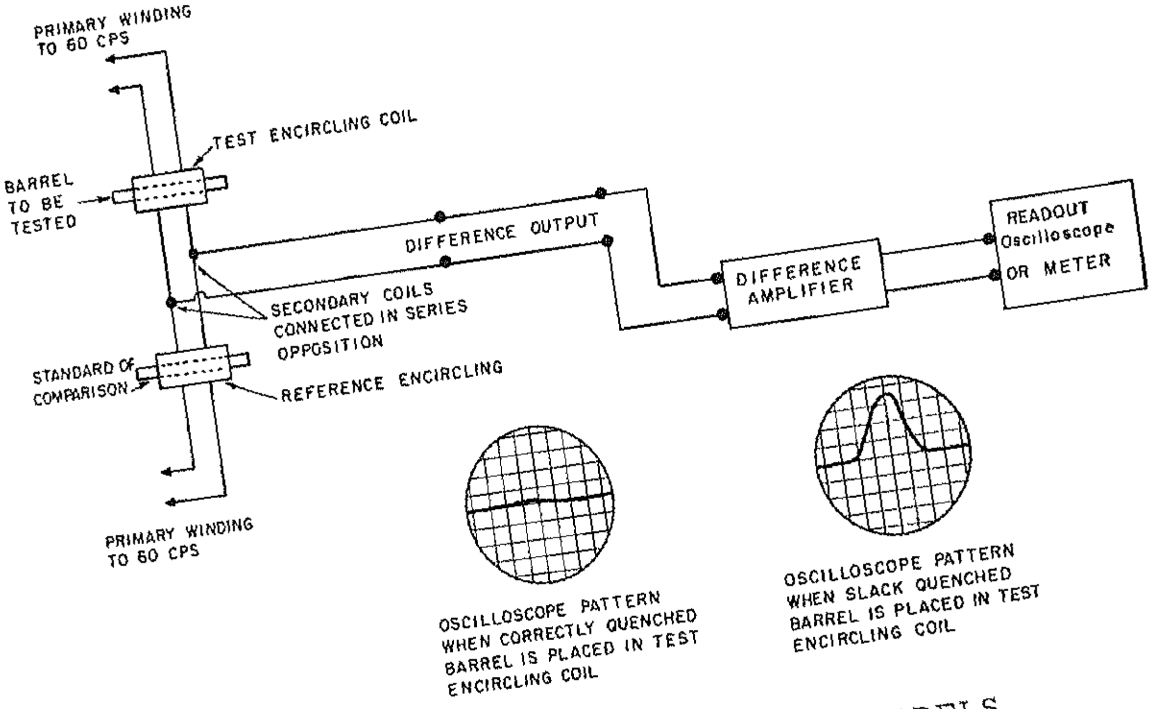


FIGURE 51. TEST SETUP FOR GUN BARRELS

39. SUMMARY

The foregoing problem was examined for several important features. The specimen was ferromagnetic; this meant that both the permeability and conductivity of the barrels would vary according to the heat treatment process. A slack-quenched barrel would, therefore, be expected to produce the larger core loss (eddy current and hysteresis losses combined). This loss would result in a different voltage being developed across the secondary of a coil encircling the barrels 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, properly quenched barrel, and the difference between these two voltages would be amplified and displayed in the readout subsystem. The displayed voltage, therefore, could be related to the metallurgical difference between the test barrel and the standard of comparison barrel.

CHAPTER 4

EQUIPMENT CALIBRATION AND QUALITY ASSURANCE STANDARDS

Section I. GENERAL

40. GENERAL

a. In using electromagnetic test methods for the inspection of materials or items, it is essential that adequate standards be available to (1) make sure that the equipment is functioning properly and is picking up imperfections (flaws), and (2) to ascertain whether the imperfections are cause for rejection of the sample (defects). These imperfections are any deviation from the norm specified for a particular material or item. They may be due to discontinuities, inhomogeneities, deviations in physical, mechanical, or geometrical properties, heat treatment, or any of a variety of causes. Before proceeding in this discussion of standards, it would be well to point out the difference between a FLAW and a DEFECT. A FLAW is any imperfection in a material or item which may or may not be harmful. A DEFECT, on the other hand, is any imperfection in a material or item which is cause for rejection. Hence, a defect is always a flaw but a flaw is not necessarily a defect.

b. It is not the imperfection itself that is detected by the test equipment, but rather the effect that it has on the electromagnetic properties of the piece being inspected. It is necessary, therefore, that it be possible to correlate the change in electromagnetic properties with the cause of the change. For this reason, it is necessary, when calibrating an electromagnetic testing unit, that standards be available that contain either natural or artificial imperfections which can accurately reproduce that change in the electromagnetic characteristics which can be expected when production items containing flaws are tested. Such standards are usually considered equipment calibration standards. That is, they demonstrate that the equipment is, in fact, picking up the imperfection or imperfections for which the material or item is being inspected.

These standards are not only used to facilitate the initial adjustment or calibration of the test instrument, but also used periodically to check on the reproducibility of the measurements.

c. It is not enough just to be able to locate imperfections in a test piece; the inspector must also be able to determine if the flaw is severe enough to be cause for rejection of the item. That is, if the flaw is, in fact, a defect. For this purpose, quality assurance standards are required against which the test instrument can be calibrated to show the limits of acceptability or rejectability for any particular flaw. It is normally the responsibility of the quality assurance design engineer to specify these limits.

Once these are established, quality assurance standards are either select from actual production items representing the limits of acceptability, or samples are prepaired containing artificial flaws which serve the same purpose.

d. Although electromagnetic test equipment calibration standards hav been developed on an independent basis by various organizations, and quality assurance standards for various products have been proposed, no of these have received general acceptance. The usual practice is to deve separate sets of standards for each inspection problem encountered.

41. FACTORS AFFECTING MEASUREMENT OF DISCONTINUITIES

a. To differentiate, electromagnetically, between an acceptable and a rejectable discontinuity, it is first necessary to understand how eddy currents actually measure a discontinuity. The question might be asked whether eddy currents measure depth or length, or some other dimension or a combination of dimensions.

In testing tubing, for example, if the test frequency is low enough and the test coil wide enough to induce eddy currents more or less uniformly throughout the wall of a given section, then the response of the electromagnetic test instrument does bear a relationship to the depth of the discontinuity. Given two drill-holes of the same diameter in the tube wall, one twice as deep as the other, the instrument response to the deeper one will be about twice as great as the response to the shallower one. This is shown for three 0.014 inch diameter drill holes of different depth in figure 52. However, if the hole diameter rather than its depth were doubled, the response again would be about double. Thus, it is neither depth alone nor width alone, but rather an area related to the product of he two which is important.

b. More precisely, instrument response is a function of the area of the discontinuity (within the range of the eddy currents) projected on a plane perpendicular to the eddy current paths. This depends partly on the orientation of the discontinuity. In the hypothetical case of a discontinuity which is perpendicular to the current paths lying entirely within the range of the eddy currents, and which is infinitely thin, the area seen by the eddy currents is approximately equal to the true area of the discontinuity.

c. Several correction factors, however, must be applied to this relationship between the measured and the true area of discontinuity to make it exact. One correction factor has to do with a secondary effect of the volume or shape. For example, a spherical inclusion and a narrow crack nay have the same projected area but affect currents differently.

second correction factor results from the fact that the eddy current ensity is not usually uniform over the entire cross section of the discontinuity, but decreases rapidly with depth into the metal (skin effect) as well as with axial distance away from the center of the test coil. The adial and axial rate of change of eddy current density depends on test

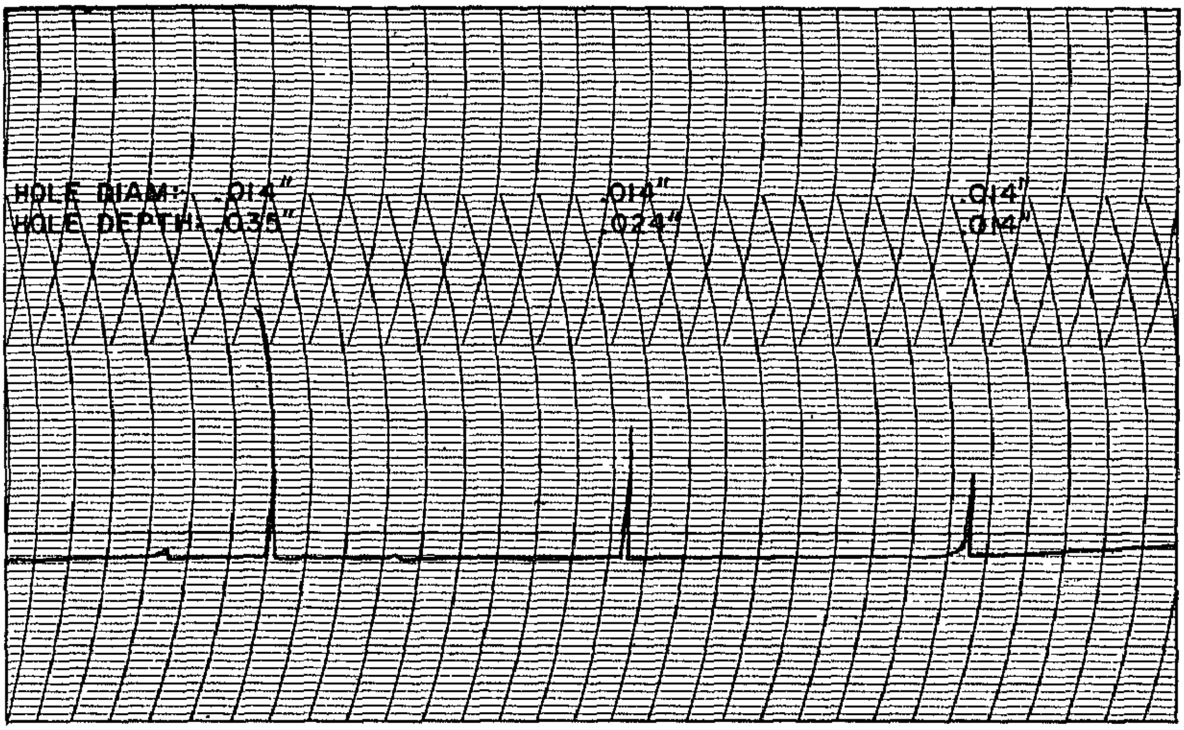


FIGURE 52. RESPONSE OF AN ELECTROMAGNETIC TEST INSTRUMENT TO THREE 0.014-INCH DRILL-HOLES TO A DEPTH OF 0.035-INCH, 0.024-INCH, AND 0.014-INCH, RESPECTIVELY, IN A 0.500-INCH TUBE HAVING A WALL THICKNESS OF 0.035-INCH

frequency and test coil dimensions. A third correction factor results from the fact that the output of electromagnetic instruments is not usually direct proportional to the signal in the coil because of the various electronic processes involved. For example, the output of a phase analysis circuit is proportional to the component of the test signal in a particular phase direction. Also, the phase analyzed signal may be modulation analyzed. Modulation analysis channels pass signals which have a certain rate of change while suppressing those with another rate of change. While the analysis circuits are indispensible in removing the unwanted variables, they also serve to complicate the relationship between the output of the test instrument and the magnitude of the original discontinuity area.

d. From the foregoing discussion, it can be seen that there are many factors to be considered when standards are to be chosen for equipment calibration and quality assurance purposes. The rest of this chapter will deal with the preparation and use of suitable standards.

Section II. EQUIPMENT CALIBRATION STANDARDS

42. FUNCTION

As stated previously (par. 40), the function of an equipment calibration standard is to qualify a test instrument and the associated methods and procedures involved, including the test frequency, test coil(s), phase setting, and other instrument settings pertinent to a particular test. A calibration standard is normally used only at the beginning of an inspection run on a new material or item, or when new specifications are introduced. A quality assurance standard, on the other hand, is used at regular intervals throughout a run to check on the reproducibility of results. Calibration standards aid in adjusting instrument controls and are used to assure that particular types of flaws, which are of interest, will be detected with a predetermined sensitivity relative to other types of flaws and conditions.

43. GENERAL CONSIDERATIONS

An equipment calibration standard should be prepared from sound material of sufficient size as to preclude the undesirable effects of ends and edges, and should otherwise be identical to the material to be tested. It is necessary that a standard of any kind be capable of exact duplication by others in the field. This requirement rules out the possibility of using a calibration standard with naturally occurring flaws and limits the standard to artificial discontinuities. There are no restrictions, however, on the size, shape, or position of the artificial flaws except that their design be such that they be exactly reproducible.

44. DESIGN CONSIDERATIONS

a. Generally, calibration standards are designed to not only contain a variety of flaws, but also to duplicate the normal characteristics of the actual test material or item. Artificial flaws are intended to simulate as closely as possible the types and positions of actual flaws; for example, notches used to simulate cracks. Characteristics inherent in the test piece, such as mechanical properties or geometrical variations, are duplicated as nearly as possible in the standard. Usually, these characteristics are of no interest to the test and must be suppressed during testing. Therefore, it is necessary when calibrating the test instrument, to allow for the suppression of signals from these characteristics.

b. There are several methods available for simulating natural flaws when preparing calibration standards. Such methods include: (1) electric discharge machining, (2) filing, (3) drilling, (4) milling, (5) scribing, (6) gouging, and (7) chemical etching. Simulated flaws which may be produced by the above methods include: (1) longitudinal notches, (2) circumferential notches, (3) drilled holes, (4) file cuts, (5) pits, (6) diameter steps, (7) indentations, and (8) intergranular corrosion.

c. The types of artificial flaws selected for inclusion in the calibration standard may be produced in any specified and practical number, position, and size consistent with the aims and objectives of the calibration procedure. Use of a standard to qualify a test instrument, or to choose between several instruments, requires some knowledge of the many variables encountered in electromagnetic testing and how they affect the test instrument. When setting up a test using a calibration standard, all combinations of test frequencies and instrument settings should be tried to determine the optimum combination which best serves the aims of the test.

Section III. QUALITY ASSURANCE STANDARDS

45. FUNCTION

A quality assurance standard performs a function which is altogether different than that of an equipment calibration standard. While the calibration standard shows what the instrument can do under a certain adjustment, the quality assurance standard seeks to keep this level of performance, whatever it is, identical and reproducible at all times and under all conditions of time and temperature.

46. GENERAL CONSIDERATIONS

Since a quality assurance standard does not need to prove that a certain type of defect can be detected, such proof having been provided by the calibration standard, the artificial flaws placed in the calibration standard do not necessarily have to simulate natural defects. Nor do they need to be present in as great a number or variety. They must, however, be of such a nature as to reveal drifts of both the amplitude and phase sensitivity of the instrument.

47. DESIGN CONSIDERATIONS

a. Amplitude stability can be guaranteed by means of two artificial flaws, one slightly larger than a chosen "borderline" size (i. e., just barely acceptable), the other slightly smaller than this "borderline". This will allow the sensitivity control on the instrument to be adjusted so that during testing all flaws producing instrument outputs larger than the chosen borderline size will be rejected and all others accepted. To achieve amplitude stability, it is possible to use any two discontinuities no matter how dissimilar they may be to the actual natural flaws to be detected. However, it becomes extremely important to control the exact dimensions of these discontinuities in accordance with the specifications on the borderline discontinuity amplitude. For these reasons, it is practical to choose a type of flaw which may be produced easily to precisely specified dimensions. If time does not permit the preparation of a more accurate standard, a simple amplitude calibration standard may be made, using two cuts produced by a hand file. The cuts may be trimmed and pared until, when the instrument is being adjusted, the larger file cut triggers the alarms and the smaller one does not.

b. In preparing a quality assurance standard, the ultimate choice of he size of the artificial borderline discontinuity, should be made only fter a careful destructive examination of a number of test samples checked with an electromagnetic instrument and found to contain natural flaws. The destructive tests will show which size flaws are actually defects, and hence cause for rejection of the test piece, and which size can be considered as not defects. The reliability of the results will depend on the number and size of flaws studied. Recorder charts should be kept for each test with the instrument settings carefully recorded. Test objects which show an indication that a flaw may be present, should be sectioned and examined metallographically, in order that the type, shape, size, and location of the discontinuity can be determined. This will provide the correlation between the electromagnetic characeristics of natural and artificial flaws so necessary in arriving at uitable test specifications.

c. To control phase stability in instruments capable of measuring ase relationships, a third simulated flaw must be introduced in the quality assurance standard. This flaw must:

(1) produce an instrument response about equal in magnitude to the borderline discontinuity, and

(2) produce a signal in the test coil as different in phase direction as possible from the two discontinuities used for amplitude stability control.

Condition (2) above requires that this third discontinuity have either a different shape or a different depth than the other two. In the case of tubing where the first two flaws are in the outside diameter, the third flaw should be located on the inside diameter wall if convenient and practical. If this is not possible, the following combination of discontinuities may be used:

If the first two discontinuities are

(1) drill-holes entirely through the tube wall,

(2) narrow longitudinal notches on the outside diameter, or

(3) indentations on the outside diameter,

then the third discontinuity may be either

(1) a shallow file cut,

(2) a circumferential ring notch,

(3) a diameter step,

(4) a narrow deep notch, or

(5) a drill-hole through the tubing wall.

Section IV. PREPARATION OF STANDARDS

48. GENERAL

a. Specimens selected for standards should be of convenient size in order to eliminate edge effects, and should be as free from natural imperfections as possible so confusion will not arise in the identification of instrument response to artificial flaws. In addition, the standards should be identical to the test objects being tested as far as chemical composition, heat treatment, physical and mechanical characteristics, shape (geometry), and temperature are concerned. If the standards and test objects are made of ferromagnetic material, they should be in a demagnetized state before the calibration or test. These factors are particularly important in the matter of such sources of "part noise" as dimensional fluctuations, residual stresses, surface roughness, and straightness. The term, "part noise" is used here to denote the undesired extraneous information which appears in the resultant test signal at the instrument readout.

b. The identification of instrument response is greatly simplified if the discontinuities are spaced at uniform distances from each other. An exception is the equipment calibration standard designed to test resolution; this type uses several closely spaced artificial flaws. An important matter, relating especially to longitudinal notches, is the choice of their length as compared to the width and spacing of the windings of the test coil configuration. This consideration is particularly important when a differential coil system is used with the two pickup coils arranged coaxially so that the equipment calibration standard passes through both pickup coils, with one section of the standard being compared to an adjacent section of the same standard. The differential test coil configuration is not very sensitive to gradual changes in diameter or structural properties, but is very sensitive to short discontinuities as cracks, seams, or artificial flaws. If discontinuities, which are uniform or nearly uniform along their length such as longitudinal notches, are long enough to extend through both pickup coils, this technique will not reveal the presence of the discontinuity except when the discontinuity enters or leaves the coil system. The configuration and frequency of the exciting and pickup coils must, therefore, be varied to suit the resolution requirements.

49. METALLOGRAPHIC EXAMINATION

a. Before a sample containing a flaw is examined metallographically, it is first necessary to pinpoint the exact location of the flaw on or within the sample. This is no problem when the flaw is located on the surface of the specimen and is plainly visible. However, a great many of the discontinuities of interest are located below the surface. Therefore, when a specimen suspected of containing a flaw is scanned electromagnetically and an unknown instrument response is noted, the exact location where the response occurs should be marked on the specimen.

b. When the exact location of a flaw in any given sample has been determined, the flaw is then very carefully examined to determine its various characteristics. A procedure employed for the metallographic examination of discontinuities detected and exactly located in two lengths of 0.500 inch diameter stainless steel tubing is given below:

(1) The section of the tubing wall containing the discontinuity is removed and flattened. It is then mounted flat, face up, in a metallographic mount and etched about 0.002-inch at a time. After each etching, the metal is examined under a microscope. As soon as the discontinuity appears, a photomicrographic recor

is maintained of its development with the depth-of-etch into the wall so that a complete picture of its shape and size is obtained.

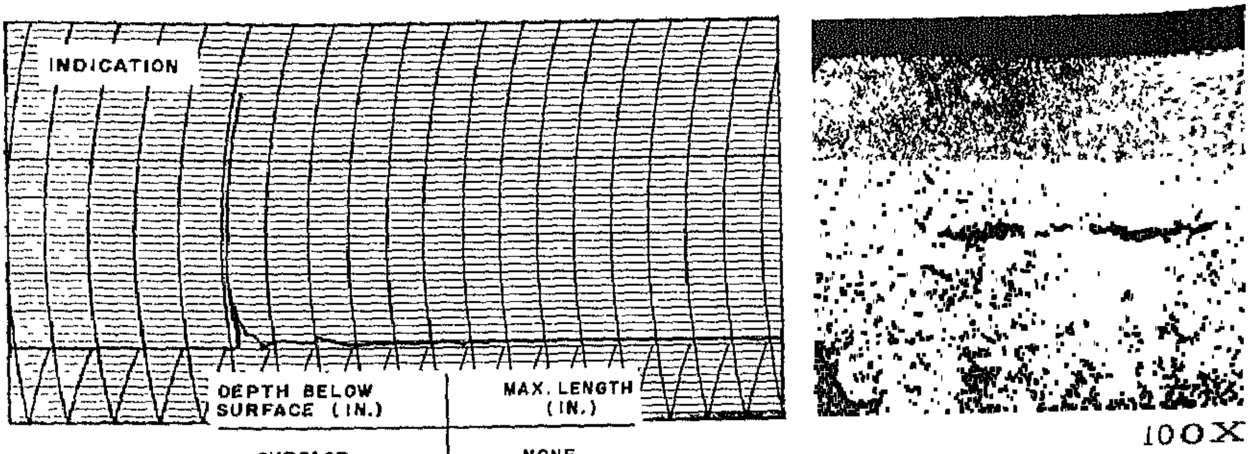
(2) The results obtained using this procedure are shown in figures 53 and 54. Each figure contains a chart record of the response of a particular electromagnetic test instrument to the small inclusion and crack found in each tube. The flaw area was pinpointed, sectioned, flattened, mounted and etched according to the above procedure. The development of each flaw with depth-of-etch from the outer tube surface is shown in accompanying tables. Several photomicrographs were taken at various depths, only one of which is shown in each figure. The defect in figure 53 was an inclusion, partly visible at the surface. The photomicrograph shows its extent at a depth of 0.0005-inch. The defect in figure 54 was a subsurface crack which reached its greatest expanse of 0.025 inch at a depth of 0.009 inch. The photomicrograph shows it at this point. Without exception, the metallographic examination found a discontinuity in every location indicated by the test instrument.

50. CORRELATION OF RESULTS OBTAINED FROM BOTH NATURAL AN ARTIFICIAL DEFECTS

a. When preparing quality assurance standards, enough natural flaws should be located and examined to find at least one flaw in each of the several categories of defects encountered (cracks, inclusions, seams, laps, etc.), which can be judged to be about borderline in severity. In other words, in each flaw class, one is chosen such that all smaller flaws may be considered acceptable. Normally, there will be no attempt to draw the line exactly. Obviously a flaw does not suddenly become failure-prone (i.e., a defect) beyond a certain specific size. The choice must be made approximately, based on whatever is known about the mechanism of failure of the part in service. The next step is to determine the relative instrument response of the borderline case chosen from each class of natural flaws as compared to known artificial flaws. This is done by noting the amplitude of the instrument response on the chart records, which should be kept on each flaw sectioned. It is important that the records to be compared be taken at identical instrument settings.

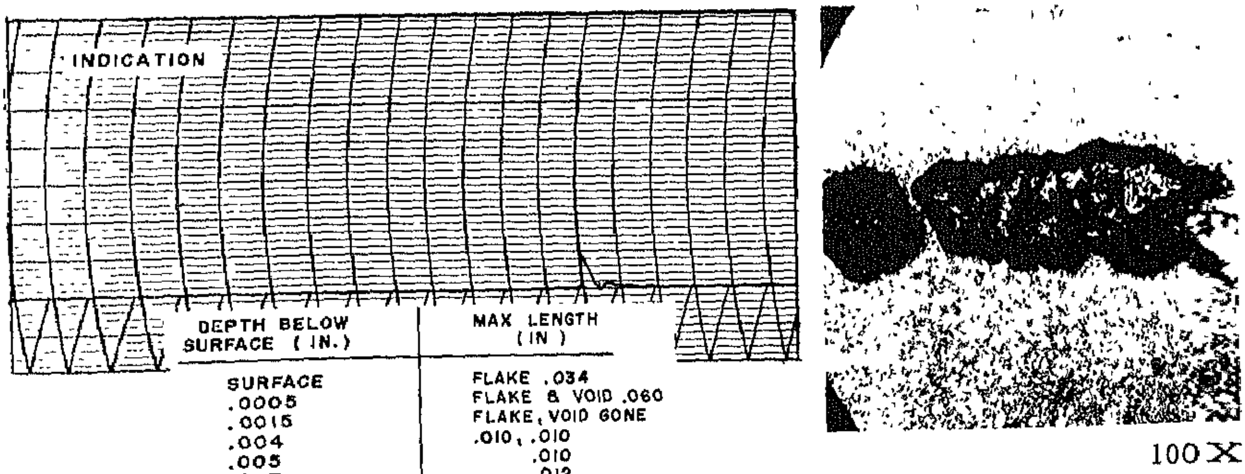
b. The flaws chosen as borderline in the different defect classes may have widely different response amplitudes. Hence a compromise must be decided upon. Once this is done, it is a relatively simple matter to choose, experimentally, an artificial defect with approximately the same response amplitude. For example, if the reference defect is to be file cut, the cut would be pared away until the response it produced reached that produced by the chosen borderline defect. Alternatively, a desired drill-hole size could be chosen from the responses obtained from a variety of drill-holes by matching the response amplitudes of the holes to the amplitude corresponding to the chosen defect. This would be the so called borderline reference defect.

The final step would be to construct a second artificial defect smaller by approximately 20 percent than the borderline defect, thus completing the construction of the calibration standard as far as amplitude calibration is concerned.



DEPTH BELOW SURFACE (IN.)	MAX. LENGTH (IN.)
SURFACE	NONE
.0005	.090
.0015	.010
.003	.015
.005	.007
.007	.006
.009	.025
011	.010
.013	.010
.015	.012

FIGURE 53. MICROGRAPHIC EXAMINATION AND ELECTRO-MAGNETIC INSTRUMENT RESPONSE TO A SMALL INCLUSION



DEPTH BELOW SURFACE (IN.)	MAX LENGTH (IN)
SURFACE	FLAKE .034
.0005	FLAKE & VOID .060
.0015	FLAKE, VOID GONE
.004	.010, .010
.005	.010
.007	.012
.0085	.012
.010	.005
.013	.010
.014	.007
.015	.010
.017	.015

IGURE 54. MICROGRAPHIC EXAMINATION AND ELECTRO-MAGNETIC INSTRUMENT TO A SMALL CRACK

CHAPTER 5

APPLICATIONS

Section I. GENERAL

51. GENERAL

a. The development of electromagnetic testing techniques in recent years has reflected many important technical advancements brought about by research activities of scientists and engineers. These activities, together with the constant expansion of the knowledge of electronics, have stimulated the selection and use of electromagnetic test techniques to a larger scale than ever. Although comparatively little use was made of electromagnetic testing techniques prior to 1950, in more recent years industry has found electromagnetic testing very useful and particularly adaptable to rapid 100 percent automatic inspection of production items and materials. The urgent need by industry to inspect bars and tubing has led to the development of a number of commercial instruments and equipment capable of handling many of the problems involved in flaw detection, hardness testing, alloy determination, and dimensional measurements.

b. In addition to this type of inspection, it has been found necessary to develop electromagnetic tests which are tailored to particular applications. Because of peculiarities in geometrical configuration, alloy composition, and the mechanical and thermal treatment of the item to be inspected, the development of electromagnetic "tests to fit the item" have presented a great variety of problems. The solutions of these problems, in many cases, have been found through pioneering efforts in test development, and have invariably required considerable study. This has been particularly true in the application of electromagnetic methods to the critical inspection of many items having high quality requirements.

52. ELECTROMAGNETIC TESTING

a. Electromagnetic testing consists of observing the interaction between electromagnetic fields and metals. The three things required for an electromagnetic test are:

(1) a coil or coils carrying an alternating current;

(2) a means of measuring the electrical properties of the coil or coils; and

(3) a metal part to be tested.

As specialized sensing elements, the test coils are in some ways analogous to lenses in an optical system, and their design is a fundamental consideration depending on the nature of the test. Probe coils which are brought up against the surface to be tested, are used in testing a variety of metallic shapes for physical properties, flaws, and plating or coating thicknesses. Annular coils encircle the part and are used especially for inspecting tubing, rod, wire and small parts (see chapters 2 and 3).

b. Electromagnetic testing involves (1) the interaction between applied and induced electromagnetic fields and (2) the imparting of energy into the test part much like the transmission of X-rays, heat, or ultrasound. Upon entering the test piece, a portion of the electromagnetic energy produced by the test coil is absorbed and converted into heat through the action of resistivity and, if the conductor is magnetic, hysteresis. The rest of the energy is stored in the electromagnetic field. As a result, the electrical properties of the test coil are altered by the properties of the part under test. Hence, the current flowing in the coil carries information about the part, its dimensions, its mechanical, metallurgical and chemical properties, and the presence of flaws.

c. The character of the interaction between the applied and induced electromagnetic fields is determined by two basically distinct phenomena within the test part:

(1) the induction of eddy currents in the metal by the applied field, figure 55a; and

(2) the action of the applied field upon the magnetic domains, if any, of the part, figure 55b.

Obviously, only the first phenomenon can act in the case of nonferromagnetic metals. In the case of ferromagnetic metals, both phenomena are present; however, the second usually has the stronger influence. This accounts for the basic difference in principle between the testing of ferromagnetic and nonferromagnetic metals.

d. Among the physical and metallurgical variables which affect electromagnetic tests in metals are the following:

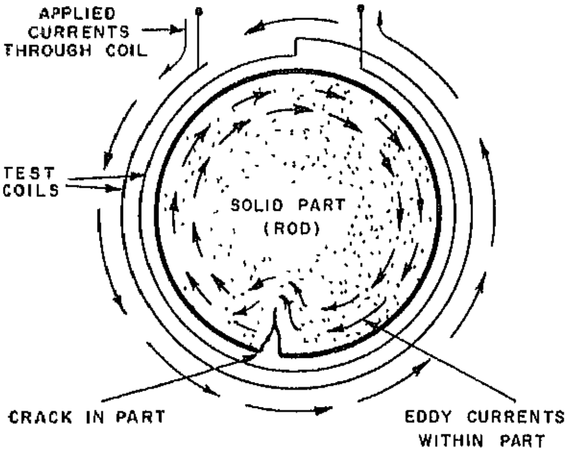
(1) Physical shape, external dimensions, and thickness of the part.

(2) Distance between part and electromagnetic coil.

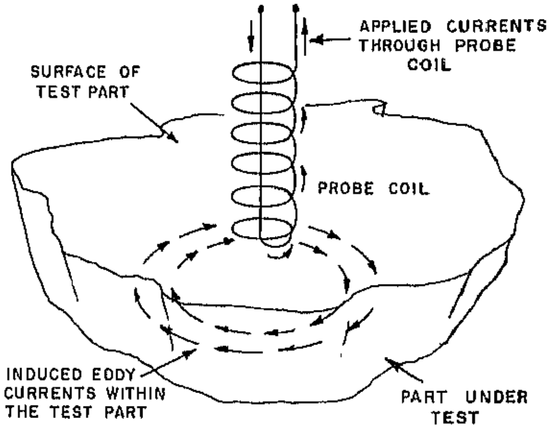
(3) Plating or coating thickness.

(4) Chemical composition.

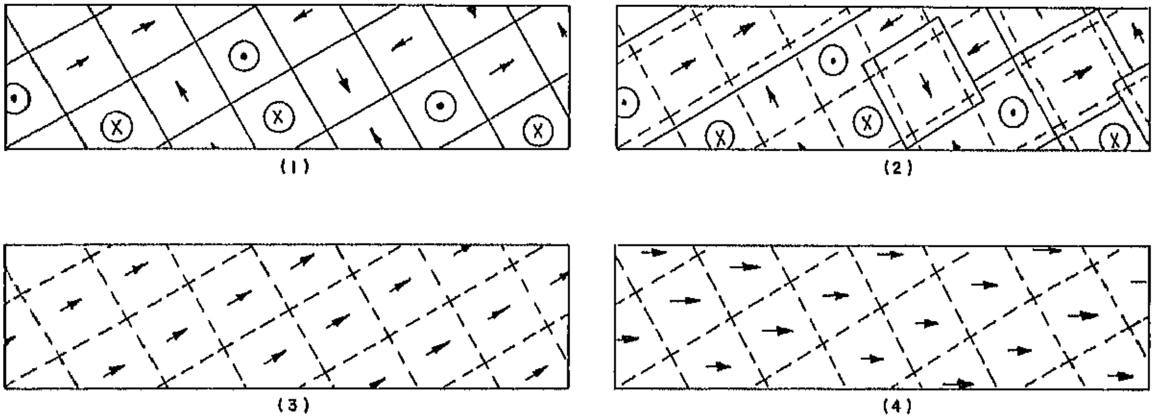
(5) Distribution of alloying or impurity atoms. This is influenced by heat treatment of the part, and hence, may be used as a clue to hardness, strength, phase, grain size, etc.



A part is passed thru a test coil. The applied current in the coil induces eddy currents within the part. These are affected by a crack, or other change in the part.



Electric currents in the probe coil induce eddy currents within the test part. These react back on the applied current for "read out".



(1) Demagnetized
(2) Partial magnetization
(3) Sudden reversals complete (knee of magnetization curve)
(4) Saturated, domains rotated in high field

FIGURE 55. DIAGRAM ILLUSTRATING CHANGES IN DOMAIN STRUCTURE IN A SINGLE CRYSTAL, IN AN INCREASING EXTERNAL FIELD DIRECTED FROM LEFT TO RIGHT. DOMAINS ARE SHOWN AS CUBES, FOR CONVENIENCE; THEY ARE BELIEVED TO BE LONG AND NARROW. ARROWS INDICATE THE DIRECTION OF THE MAGNETIC MOMENT OF EACH DOMAIN.

(6) Lattice dislocations caused by heavy working or radioactive bombardment.

(7) Temperature.

(8) Discontinuities, including most types of flaws.

(9) In ferromagnetic metals, residual and applied stresses.

In practice, many, and sometimes all, of the above factors may vary simultaneously. It is difficult under these conditions to obtain a meaningful response from the magnetic flux set up within the test piece since several variables may affect the test signal simultaneously. The resulting voltage, which is the parameter usually sensed by electromagnetic testing devices, must be very carefully analyzed to isolate the sought-after effects from the extraneous effects.

e. Associated with any electromagnetic test signal are three important parameters: amplitude, phase, and frequency. The test signal may contain either a single frequency, the test signal frequency, or a multitude of frequencies (harmonics of the test signal frequency). In the latter case, the test signal frequency is referred to as the fundamental frequency. In addition, there is an amplitude and phase parameter associated with each harmonic frequency. The control engineer has available a number of techniques that make use of all of this information that permits him to discriminate between test variables to a considerable extent. The important techniques used are amplitude discrimination, phase discrimination harmonic analysis, coil design, choice of test frequency, and magnetic saturation.

f. The uses of electromagnetic testing techniques in the ever-expanding ield of nondestructive testing can be placed into the following three general ategories:

(1) The measurement of conductivity, or a combination of conductivity and permeability. This includes the identification of metals, sorting of metals according to their mechanical and thermal history, and the measurement of other metallurgical variables which affect the conductivity and permeability.

(2) The measurement of the thickness of thin metal sections, the measurement of the cladding or shrouding thickness of one metal on or around another, and the measurement of the thickness of nonmetallic coatings on metals.

(3) The detection and evaluation of both surface and internal discontinuities and other conditions relating to metal quality.

ithin these three general areas of effectiveness, lie many nondestructive sting problems.

g. The fundamental concepts which govern the development and application of electromagnetic tests for both ferromagnetic and nonferromagnetic materials are essentially the same. However, because of the large effects produced by the magnetic permeability (in particular) and other similar nonlinear magnetic properties (in general) of ferromagnetic materials, the nature and solution of the problems encountered in practice are often quite different for the two types of materials. These differences are such that, in any detailed treatment of the subject, discussions are qualified to apply to either ferromagnetic or nonferromagnetic testing.

h. For purposes of this discussion, electromagnetic test applications will cover two general areas:

(1) tests for specific properties including tests for uniformity and composition, carbon content, heat treatment, case depth, hardness, and strain; and

(2) tests for discontinuities and inhomogeneities according to specimen geometry including the inspection of tubes, rod, wire, sheet, plate, measurement of thickness, and end items.

Because each test involves straightforward scanning of the test part surface by a test coil or coils either manually or by mechanical methods, emphasis shall be placed upon the results of illustrative test examples.

Section II. TESTS FOR SPECIFIC PROPERTIES

53. GENERAL

a. Progress in the metal working industry is closely related to advanc ments in quality assurance inspection methods. Before putting a product into mass production, there should be available an easy, rapid, and inexpensive means of measuring its degree of acceptability. One of the various ways in which this can be accomplished is by the use of electromagnetic test instruments. These instruments provide a fast and nondestructive method for the accurate inspection of ferrous and nonferrous materials, for variations in composition, condition, structure, and processing.

b. Electromagnetic instruments have found wide use as accurate "go-no-go" gages in various inspection applications involving the sorting of materials according to specific properties. For this application, two representative pieces are chosen corresponding to the low and high limits, and the unknown piece is then compared with the readings on the two limit pieces. If the reading falls between the two limits, then the piece being checked is acceptable. If it falls outside these limits, it is rejected. This type of setup permits extremely accurate, rapid, and inexpensive checking of an entire production run.

c. The following conditions should be considered in selecting standard specimens:

(1) The standard specimen must be the same size and shape as the piece to be tested.

(2) Standard specimens must have the same heat treatment as the piece to be tested.

(3) Surface finish must be the same. If test pieces are ground, standards must be ground. If test pieces are cadmium plated or surface finished with any other metallic coating, standards must also be coated.

(4) Cold bends in long bars or rods set up local high internal stresses which may confuse test results.

(5) Care must be taken in choosing a specimen to represent "spotty" bar stock which may have local hard or soft spots.

(6) If the pieces to be tested are long and of uniform cross-section such as angles, bars, rods and tubes, the length of standard or test piece does not matter as long as it exceeds a minimum length for which no end-effects are produced, especially when the pieces are ferromagnetic.

(7) Two or three standard specimens of each particular composition or treatment should be available to avoid the effects of overheating which occur if a single standard specimen were to be used continuously. If a single standard specimen is used, arrangements should be made to cool it; for example, with a stream of air. The heat is generated partly by hysteresis losses, but mainly by eddy current losses.

54. TESTS FOR COMPOSITION AND UNIFORMITY

a. Ferromagnetic Materials.

(1) Chemical composition exerts a strong influence on the magnetic properties of steel. Table II (chapter 2) shows how the magnetic properties of a cobalt-chromium-molybdenum steel are affected when the cobalt content is varied. Increasing the carbon content of any ferrous material increases the coercivity, resistivity and retentivity, and reduces the permeability and saturation flux density of the material. As a direct consequence, a broadening and an increase in the area of the hysteresis loop occurs and results in an increase in the hysteresis loss value. Heat treatments for steel hardening can cause these effects to become more pronounced. Another striking effect is that produced in some steels by an increase in the nickel content. The saturation flux density is greatly reduced, and at 30 percent nickel, the steel becomes completely nonmagnetic.

(2) Cold working of ferromagnetic materials reduces the magnetic properties, but gives a high value for hysteresis loss, a particularly undesirable condition in steels called upon to operate in alternating magnetic fields. The effects of cold working on the magnetic properties of 4 percent silicon steel and of impurities on the hysteresis loss of iron are shown in figure 56.

(3) Sorting of steels on a basis of composition or heat treatment is complicated by other factors which affect the magnetic characteristics. The effect of size is the most important, but in the case of mass-produced components, this trouble should not arise. Position of the specimens in the test coils is of particular importance as their location must be as nearly identical as possible in each test. Once the size and location of the specimen is standardized, the main variables are composition and/or heat treatment, and in most cases sorting can then be done satisfactorily.

(4) Sorting and comparison methods of testing can be based on magnetic induction curves and the quantities derived from them. Differences between materials can be detected by measurement of values of maximum intrinsic flux density (B_m), the magnetizing force for fixed values of flux density (H), the coercive force (H_c), maximum permeability (μ_m), the values of retentivity, or by measurement of hysteresis loss.

(5) In all work on magnetic sorting, it has been shown that separations can only be accomplished when one variable changes significantly. In the event of a number of variables being present, a preliminary sorting into groups to isolate each in turn is essential.

(6) Basically, all electromagnetic test instruments used depend on some correlation between the magnetic and physical properties of a ferromagnetic material. Seldom is there a direct correlation between a given set of magnetic properties and a desired set of physical properties. The problem of devising a practical test consists of finding some easily and quickly measured set of magnetic properties which will give a practical correlation with physical properties, such as composition, hardness or strength.

(7) A series of steels whose compositions were stepped to give a range of carbon, manganese, and silicon contents was examined using a typical electromagnetic sorting instrument. Representative traces obtained with various pairs of specimens are shown in figure 57. Distinctive patterns were obtained with differing carbon and manganese contents, although small changes in the latter were not well shown and could be confused with changes in the carbon content. Differences in sulfur content could only

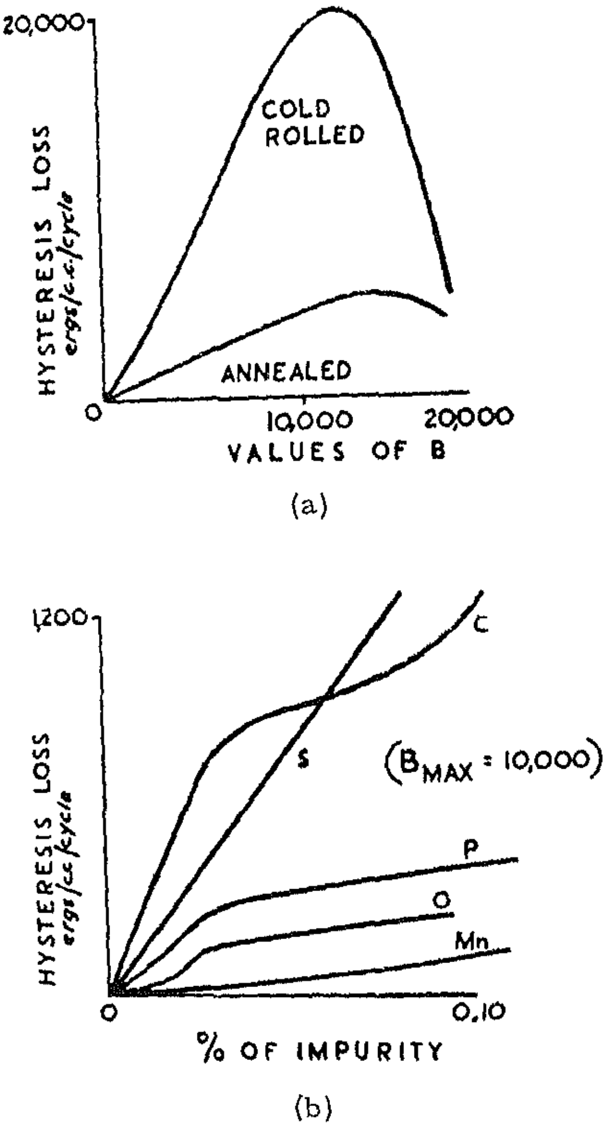


FIGURE 56. (a) THE EFFECT OF SEVERE COLD WORK ON THE MAGNETIC PROPERTIES OF A 4% SILICON STEEL, (b) THE EFFECT OF IMPURITIES ON THE HYSTERESIS LOSS OF IRON

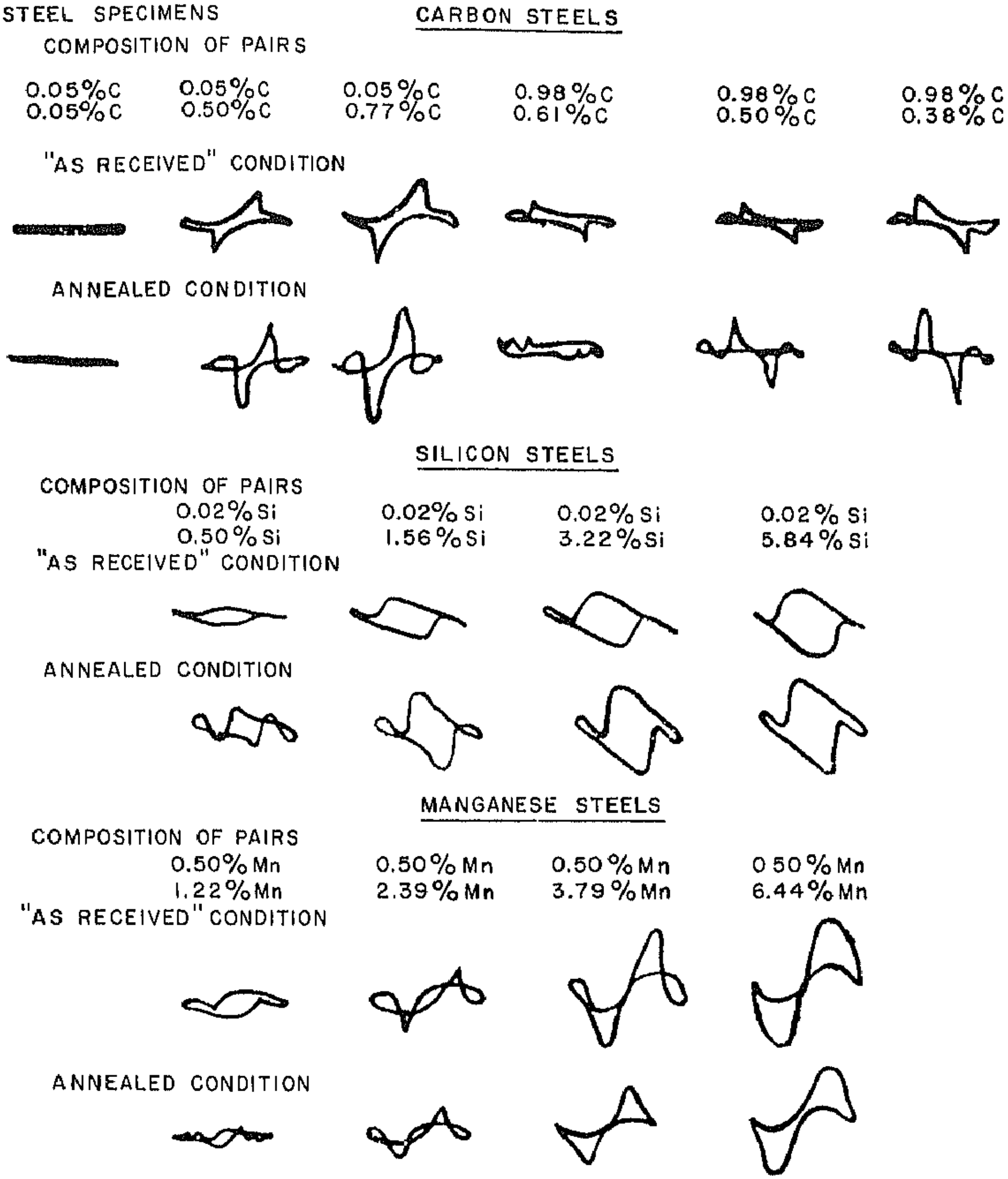


FIGURE 57. EXAMPLES OF MAGNETIC SORTING BRIDGE TRACES

be detected below certain ranges. The effect of silicon was substantially the same as that of carbon, but distinctive features were apparent with large changes of silicon content.

b. Nonferromagnetic Materials.

(1) The ability to distinguish between pure metals is not nearly as useful as the ability to distinguish between alloys of the same base metal. In manufacturing facilities where alloys of the same or differing alloy content are used, there is the ever-present problem of accidentally mixing different types. Incoming inspection also has a problem of identifying various alloys, since the supplier of raw materials is also apt to make mistakes.

(2) Most nonferromagnetic pure metals can be readily distinguished from one another by their conductivities expressed directly in terms of percent of International Annealed Copper Standard or %IACS. Standard conductivity has been defined by the International Electrotechnical Commission in terms of the amount of resistance to be found in a specific grade of high purity copper when measured at 20°C (68°F). This resistance amounts to approximately 0.15 ohms per gram-meter and has been arbitrarily designated as 100% conductivity. For example, pure lead has a conductivity of 8 to 9 %IACS. Gold ranges from 72 to 77 %IACS. Tungsten is found in the range from 31 to 32 %IACS. Silver will be found at approximately 102 %IACS. An accompanying chart, figure 58, illustrates some of the conductivity of pure metals and a few of the more common alloys. The relatively narrow ranges of conductivities of the pure metals make it comparatively easy to sort one from the other.

(3) Almost all alloys have ranges of conductivities and frequently there is an overlapping of values. The accompanying chart, figure 59, shows a few of the light metals and their conductivity values. This overlapping cannot be avoided since it is the nature of the material which governs the conductivity. Despite occasional overlapping, conductivity is still a useful adjunct to the other tests commonly used in the identification and sorting of mixed metals and alloys.

(4) From the foregoing, it would appear that measurement and interpretation of conductivities is a simple operation. The measurement itself is quite simple; however, the interpretation is sometimes more complex than these simple figures would seem to relate. Many of the values of conductivity listed in the references indicate variations in value because metals can exist in more than one state or condition. For example, certain types of copper-chromium alloys have a conductivity ranging from 30 to 35 %IACS when measured in the wrought

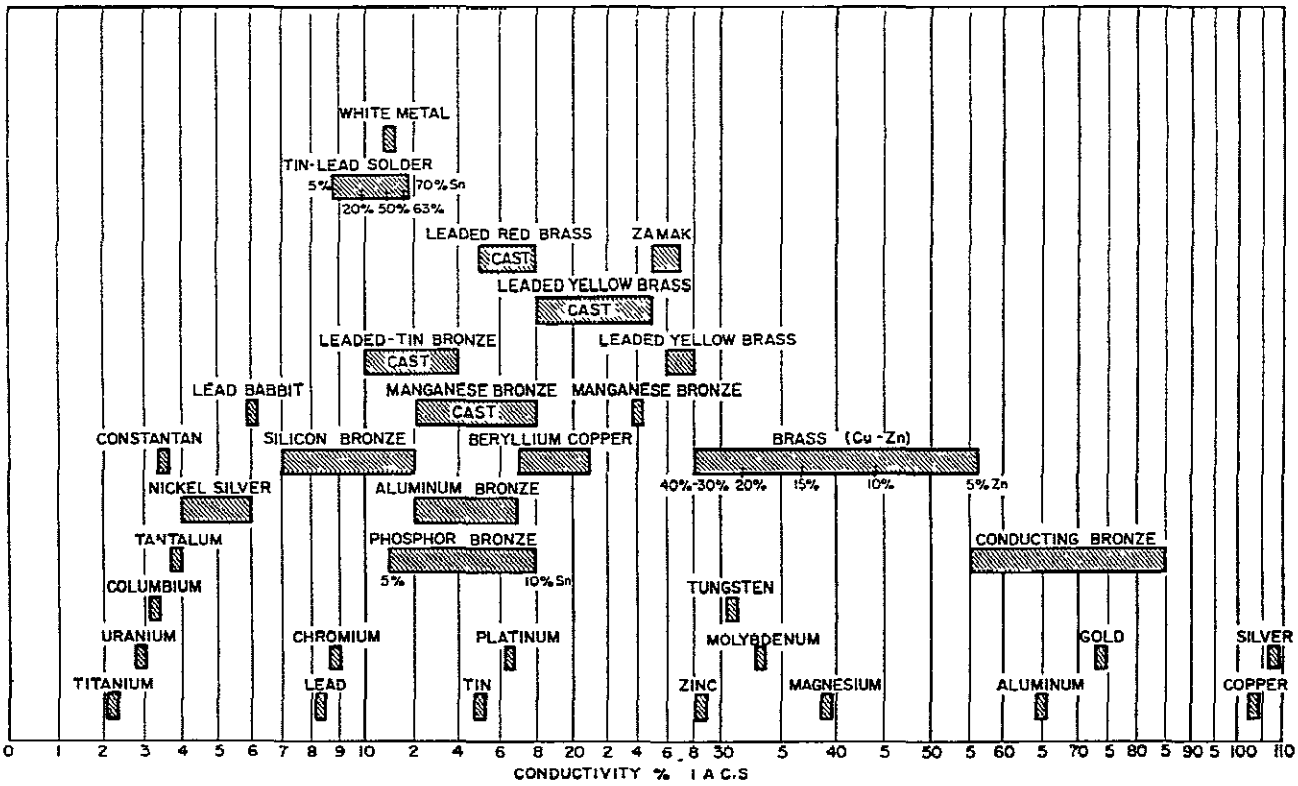


FIGURE 58. ELECTRICAL CONDUCTIVITY OF VARIOUS METALS AND ALLOYS

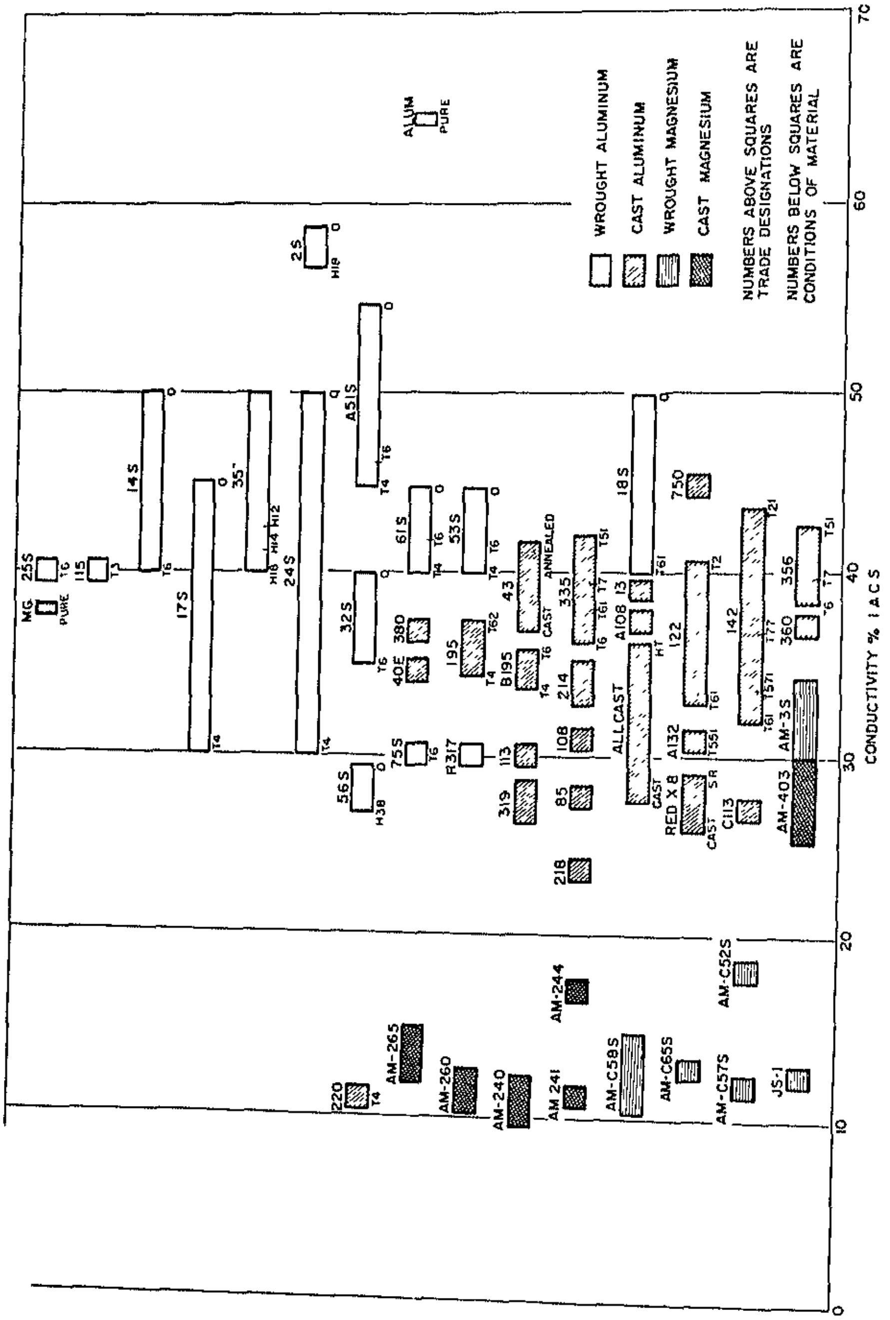


FIGURE 59. ELECTRICAL CONDUCTIVITY OF ALUMINUM AND MAGNESIUM ALLOYS

and quenched states. The same alloy, after precipitation hardening may have conductivities ranging from 80 to 90%.

(5) Figure 60 shows how the addition of small quantities of other elements to copper causes a proportional and often marked decrease in electrical conductivity. Consequently, other factors being equal, the measurement of conductivity can be used to control the addition of alloying elements or to determine the presence of impurities. A good example of the former use can be found in the control of melt quality when producing phosphorus-deoxidized copper, particularly when a comparatively high conductivity is required. A test bar, 2.50 to 3.00 inches in diameter, when cast in a chill mold and cut as soon as it is cold, can be used as a rapid test for the conductivity, and consequently the composition, of a high conductivity melt. By reference to figure 61, the phosphorus content can be rapidly and accurately determined and, if necessary, correction made to the melt before pouring.

(6) A further stage in foundry control is possible during production of high conductivity copper alloys by making use of the fact that their conductivity decreases linearly with increasing oxygen content. The flat characteristic of the curve, figure 60, in comparison with a curve for copper containing phosphorous, makes the evaluation somewhat more difficult. From the point of view of purely industrial application, the method enables a good insight to be obtained into the melting process without its being classed as an accurate analysis. Figure 62 shows a curve of electrical conductivity recorded during the melting of virgin copper under oxidizing conditions, followed by a deoxidation. At the end of oxidation, the test piece had a conductivity of 93.5 %IACS, which corresponds almost exactly to that of the copper-oxygen eutectic (oxygen content 0.37 percent). Copper phosphide was used in small quantities as a reducing agent, and consequently, samples taken during the deoxidation process revealed higher conductivities. After a sufficient amount of the reducing agent had been added, the curve reached a maximum at 99.5 %IACS, falling off as more copper phosphide was added. In normal foundry practice, deoxidation is carried beyond the maximum point, and a suitable end condition between 0.01 and 0.02 percent phosphorous is selected according to whether the charge is to be alloyed or cast directly.

(7) A disadvantage connected with measurements in the region of maximum conductivity is that gas contained in the melt may produce a fine porous structure in the cast test samples which will give an incorrect conductivity figure for the melt. An experienced founder, however, can readily detect this kind of fault by means of a simple fracture test. By using electromagnetic test apparatus, the founder can directly control the

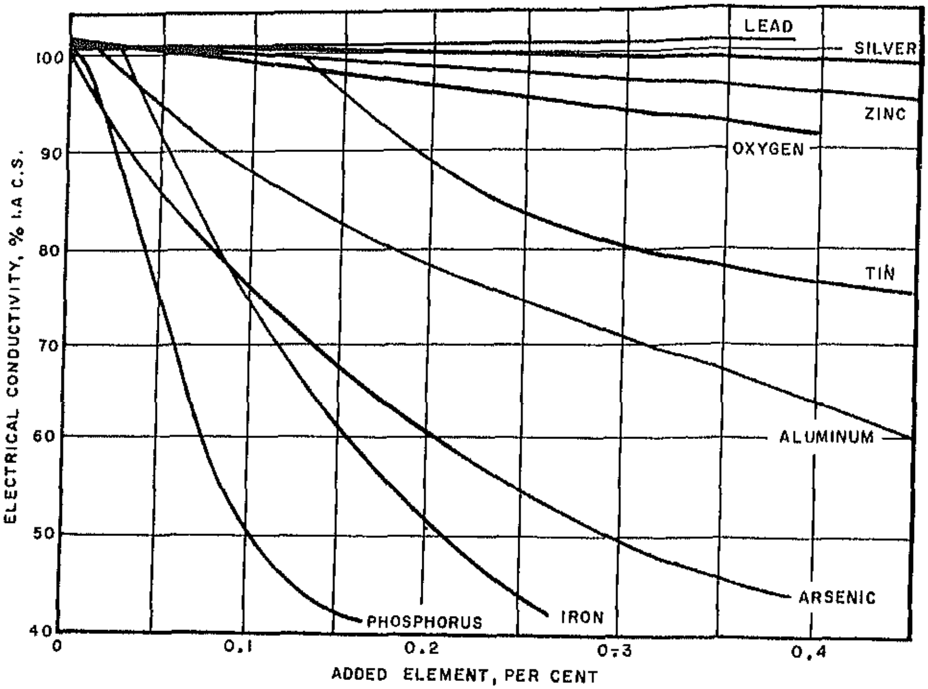
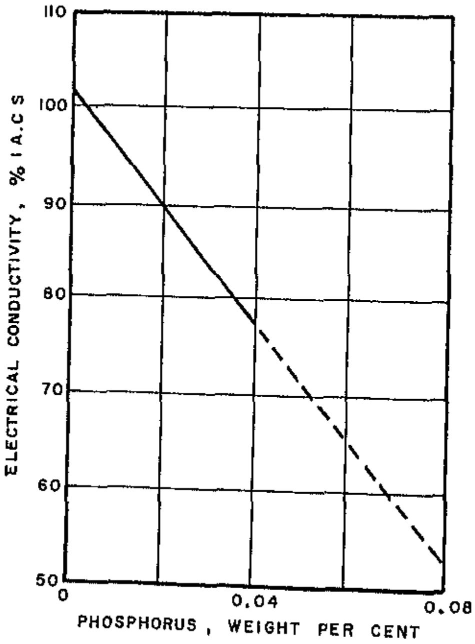


FIGURE 60. EFFECT OF ADDITIONS OF OTHER ELEMENTS ON THE CONDUCTIVITY OF COPPER



IGURE 61. EFFECT OF SMALL AMOUNTS OF PHOSPHORUS ON THE ELECTRICAL CONDUCTIVITY OF COPPER

state of the melt and, therefore, be in a better position to exploit the melting furnace more economically. It should be stressed, however, that this method must be regarded only as a practical aid, which does not replace precise analysis but offers the metallurgist a valuable and, above all, quick insight into operations at all stages of production.

5. TESTS FOR CARBON CONTENT

a. Ferromagnetic Materials.

(1) Carbon is the most important element present in any steel. The maximum hardness obtainable in a steel by quenching to a structure consisting of 100 percent martensite is governed by carbon rather than alloy content. This relationship is shown in figure 63 where it should be noted that the maximum hardness value of Rockwell C 65 occurs at a carbon content of approximately 0.55 percent. By the addition of alloying elements, the effect of carbon may be intensified, diminished, or neutralized.

(2) The relationship between carbon content of steel and its magnetic properties gives a useful method of classifying steels according to carbon content. Before the metallurgist can use an electronic instrument for this purpose, he must make sure that extraneous variables such as alloy content and heat treating history do not produce a significant change in the magnetic properties being compared, which might completely mask the desired correlation.

(3) Figures 64 and 65 illustrate the correlation between test instrument readings on standard steel test samples and their carbon content. By determining relative amplitudes and phase relation of the first and third harmonics, satisfactory correlation with carbon content is obtained on samples with 0.40 percent carbon content and over, which are all cast from the molten metal and quenched in water. On samples with less than 0.40 percent carbon which are allowed to cool slowly in the mold, no reliabl correlation is obtained because of differences in cooling rate between the hot and cold molds.

(4) The A-series of samples tested varied from 0.08 percent to 0.40 percent manganese and had the usual variations in sulfur, phosphorus, and silicon found in a series of heats of open heart steel. Only traces of chromium, nickel, molybdenum, and copper were present. These normal changes in analysis from heat to heat did not interfere with the carbon correlation.

(5) Series-B samples contained about 0.10 percent chromium, 0.50 percent nickel, and 0.07 percent molybdenum. This alloy conter

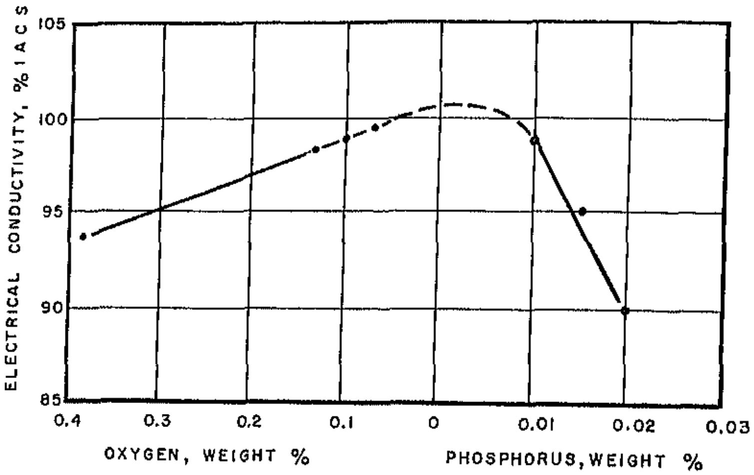
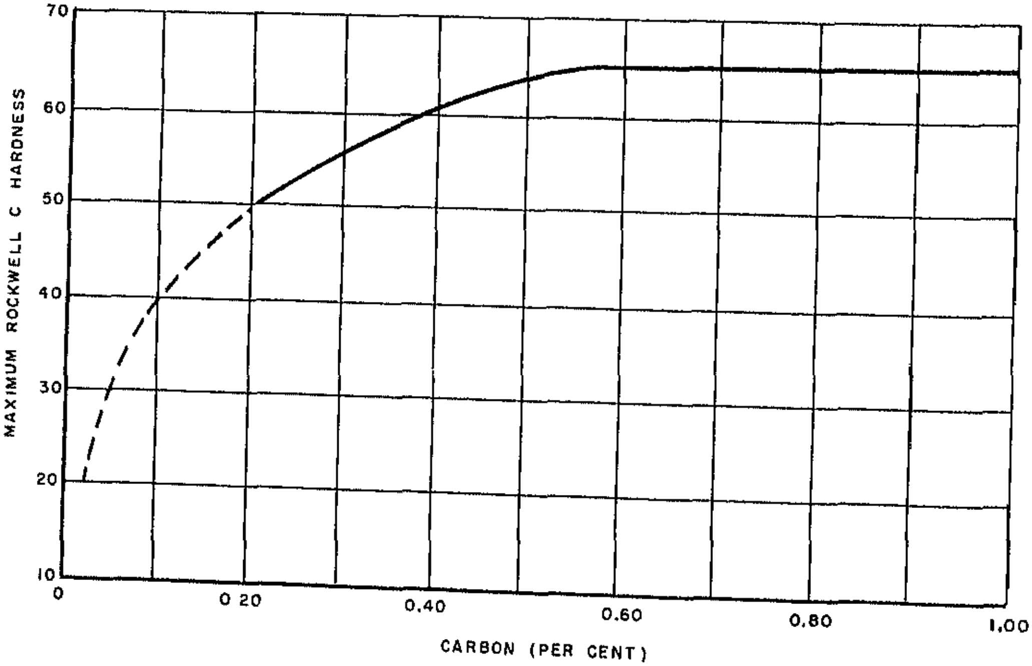
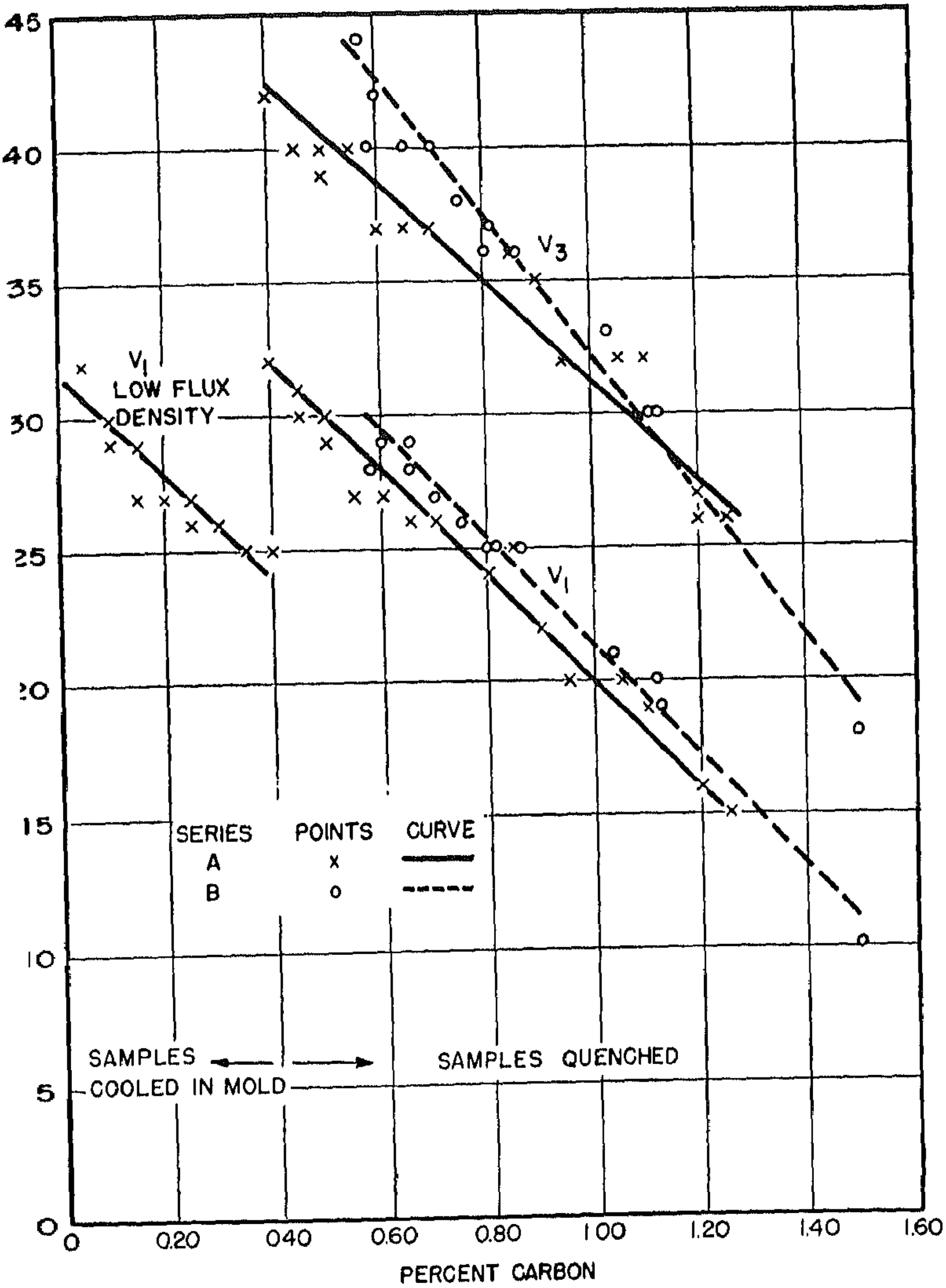


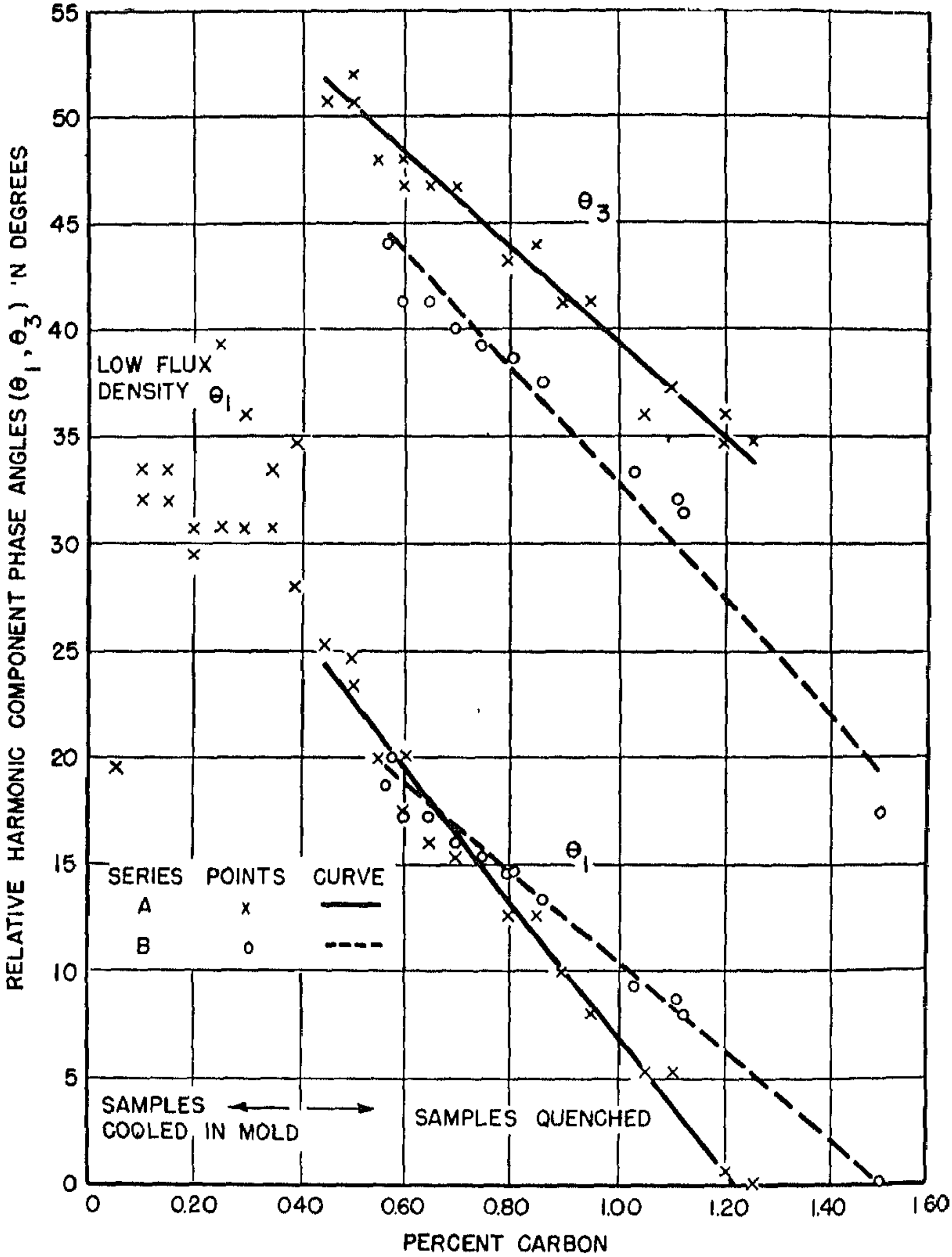
FIGURE 62. VARIATION IN CONDUCTIVITY DURING THE DEOXIDATION OF COPPER MELT



GURE 63. MAXIMUM HARDNESS VERSUS CARBON CONTENT FOR ALLOY AND CARBON STEELS



JRE 64. RELATIVE AMPLITUDES OF FUNDAMENTAL AND THIRD HARMONIC VOLTAGES VARY WITH PERCENT CARBON CONTENT OF TEST SAMPLE



URE 65. VARIATION OF PHASE ANGLE BETWEEN FUNDAMENTAL AND THIRD HARMONIC VOLTAGES INDICATES CARBON CONTENT OF SAMPLE

affects magnetic properties sufficiently to interfere with carbon correlation. Series-B samples can be identified by the test instrument and can be tested separately for carbon content. These graphs show that the instrument can correlate carbon content in samples of similar analysis, can distinguish between high and low alloy content samples, and can separate high and low alloy samples with the same carbon content.

b. Nonferromagnetic Materials. Generally speaking, the presence of carbon is of primary importance in steels (ferromagnetic materials) and is introduced in the steel formation processes to improve the physical characteristics of steel. With nonferromagnetic material, however, the presence of carbon constitutes a naturally occurring impurity and is usually considered to be a contaminant. Notable exceptions are nonmagnetic stainless steels. Because of its presence in trace amounts and its insignificant influence upon the electrical conductivity of nonferromagnetic materials, tests for carbon content are not commonly performed and hence, do not merit discussion.

56. TESTS FOR HARDNESS AND STRAIN

a. Ferromagnetic Materials.

(1) A great deal of data is available giving a correlation between magnetic properties evaluated by harmonic analysis and various metallurgical properties such as hardness, impact strength, and structure. Most of the data has been obtained on carefully prepared sets of samples in which all variables were kept constant with the exception of the one under investigation. One of the least understood points concerning the application of electromagnetic testing to the metallurgical field is that unimportant variables, usually ignored because they do not affect the service life of a metal part, may have a major effect on magnetic properties. For this reason, the translation of fundamental relationships between magnetic and physical properties into practical tests should be done very carefully.

(2) The problem of measuring hardness, utilizing electromagnetic testing techniques, is notably different than that for flaw detection. In hardness testing, changes in material properties from one specimen to another will affect the test results while in flaw detection, it may be possible to provide discriminatory techniques to minimize the effects of such "overall" average changes. Hardness testing requires test coils of only relatively simple design whereas in flaw detection, high small-area resolution is desired in conjunction with complex scanning methods. Most hardness testing methods provide two test coil configurations with an electronic comparator system. The test equipment is initially balanced with two specimens of known hardness. In subsequent tests, specimens of unknown hardness are substituted for one of the specimens. The degree of unbalance is then correlated with hardness changes.

(3) The maximum percent increase of hardness of plain carbon steels by quenching is obtained in steel containing between 0.35 and 0.70 percent carbon. Above approximately 0.55 percent carbon, there is a small increase in the hardness value obtained by quenching. Practical applications of a test for the hardness of steel components are illustrated by the two following examples:

(a) Steel bolts, 0.50 inch in diameter and 3.00 inches long, were accidentally made of two different steels, SAE 1035 and SAE 1020. The error was not discovered until after the bolts had been heat treated. The bolts made of SAE 1035 were satisfactory, but those made of lower carbon SAE 1020 were too soft. The hardness of the two lots differed by fifteen points Rockwell C. A few samples of bolts made of each steel were identified in a hardness machine. A soft bolt was placed in the instrument test coil, and the flux density and harmonic phase adjusted to give the pattern (A) of figure 66. Inserting a bolt made from SAE 1035 steel gave the pattern (B) of figure 66. The several traces in each pattern indicate the limits of variation of the patterns for fifty samples. This preliminary work established the fact that there was no overlapping of the indications for bolts made from the two steels at the flux density chosen. Sorting proceeded on the mixed bolts at a rate of about one per second.

(b) Steel bars were sorted to reject those softer than Rockwell C 32. Readings of first and third harmonic amplitude did not provide a practical separation. However, observation of the relative phases provided a sufficiently sensitive test for correlation with hardness so that the separation could be made.

(4) In many instances, one of the two types of display gives the better and more easily read indication of metallurgical differences. There is also an optimum test magnetic flux density for a particular sorting problem. A few tests at various values of energizing current will establish the most satisfactory flux density in each instance.

(5) The effects of stress on the magnetic permeability of steel is shown in figure 67, where the distinct points of the stress strain curve are shown plainly by the changes of shape at the limit of proportionality and at the apparent elastic limit. Investigation of this behavior has shown that the magnetic characteristics can provide considerable information on the small internal strains in ferromagnetic materials.

(6) Figure 68 shows the B-H curve of an unstressed bar of carbon steel superimposed on the B-H curve of the same bar under

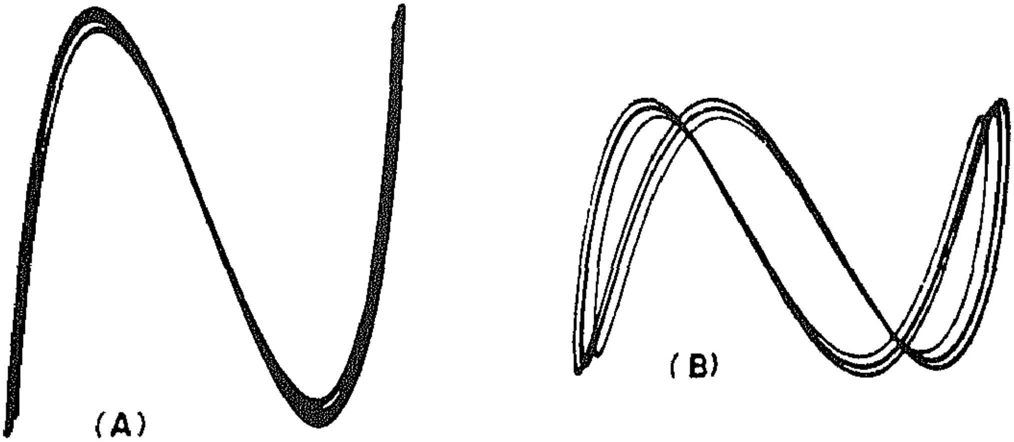


FIGURE 66. SEPARATION OF SOFT BOLTS FROM HARD ONES WAS DONE BY OBTAINING PATTERN AT (A) FOR SOFT BOLTS AND PATTERN AT (B) FOR HARD BOLTS. BOTH THE RELATIVE AMPLITUDE AND THE PHASE OF THIRD HARMONIC RELATIVE TO THE FUNDAMENTAL CHANGED TO GIVE THE INDICATION OF HARDNESS IN THIS INSTANCE

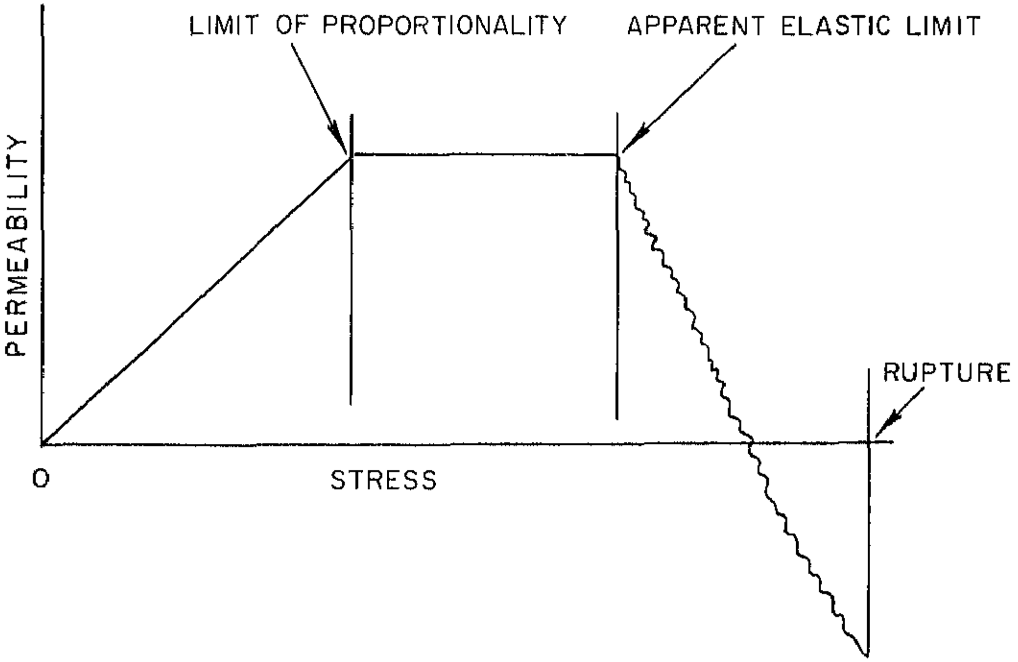


FIGURE 67. THE EFFECT OF STRESS ON THE PERMEABILITY OF A STEEL SPECIMEN

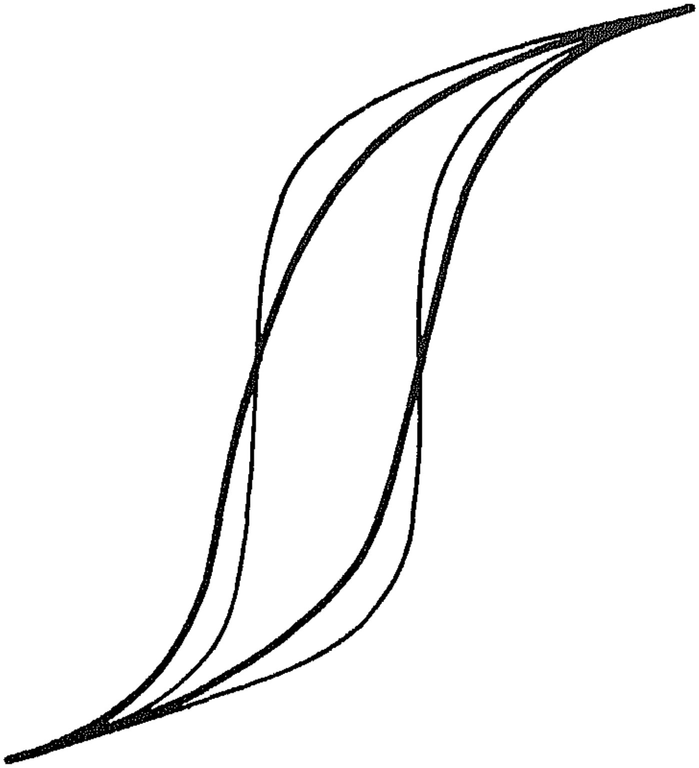


FIGURE 68. B-H CURVE OF CARBON STEEL BAR STRESSED COMPRESSIVELY TO 94,000 PSI (HEAVY CURVE) SUPERIMPOSED ON CURVE OF SAME SAMPLE UNSTRESSED (LIGHT CURVE)

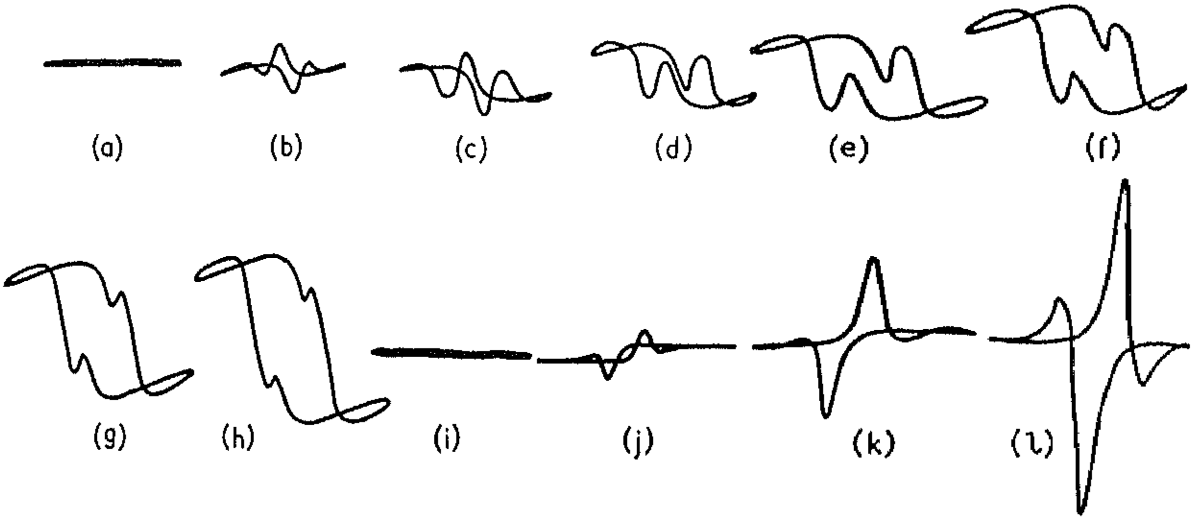


FIGURE 69. DIFFERENCE B-H CURVES FOR CARBON STEEL BAR STRESSED IN TENSION BY VARYING AMOUNTS. (a) UNSTRESSED SAMPLE; (b) 19,000 PSI; (c) 38,000 PSI; (d) 56,000 PSI; (e) 71,000 PSI; (f) 84,000 PSI; (g) 94,000 PSI; (h) 103,000 PSI (SAMPLE BREAKING); (i) TENSION RELEASED AFTER STRESSING TO 56,000 PSI; (j) RELEASED AFTER 71,000 PSI; (k) RELEASED AFTER 84,000 PSI; (l) RELEASED AFTER 94,000 PSI

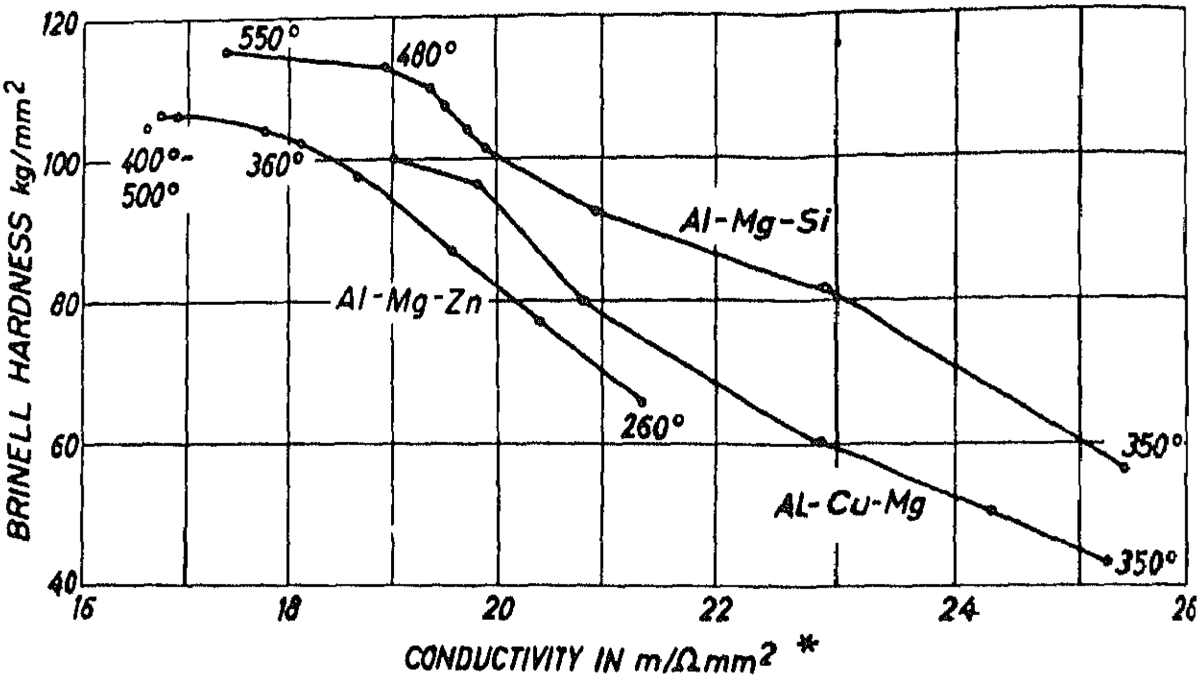
94,000 psi compressive stress. To magnify the difference between these two curves, it is convenient to subtract one from the other. This may be done by using two-coil systems, primaries connected in series, and secondaries in series opposing. In this way, the output signal consists only of the differences in voltage induced in the two secondaries. The test sample undergoing stress is placed into one primary-secondary pair; an unstressed sample of identical dimensions and material is placed in the other. The net voltage across the opposing secondaries will be proportional to the difference of conditions within the two coils and may be amplified appreciably, then integrated and displayed on an oscilloscope screen to produce the difference curves in figure 69. Curve (a) of figure 69, taken before either sample was stressed, shows only a straight line indicating that the two samples are identical. As one sample was stressed in tension by successively greater loads, the different curves (b) to (h) of figure 69 resulted.

(7) Curves (i) to (l) of figure 69 show that permanent effects, if any, had been produced by the various amounts of stress applied. Curve (i) was obtained when tension was reduced to zero after having reached 56,000 psi. It shows no changes from the initial condition of the material. Upon being released from 71,000 psi, however, the sample shows a permanent change, as shown in curve (j), indicating that the elastic limit had been passed. This residual effect becomes more pronounced as the sample is released from higher loads, as shown in curves (k) and (l).

b. Nonferromagnetic Materials.

(1) Many physical properties of the lighter metal alloys are related to their conductivity characteristics. The conductivity of aged aluminum alloys, for example, is definitely associated with hardness as is illustrated in figure 70. Hardness is a significant quality-determining property of a material and is established primarily by chemistry, heat treatment, and stress forming cold work processing. Each of these parameters can affect the electrical conductivity. Extensive use is made of the relationship between hardness and conductivity, particularly in the aircraft industry. This relationship has proven to be exceptionally useful and time saving for checking pressed parts made of aluminum-copper-magnesium alloys. Here, two calibration samples of known hardness were used to determine the range of tolerance. It was noted that the conductivity response paralleled hardness for aluminum-magnesium-zinc alloys when the materials were quenched at different temperatures. Under some conditions, conductivity was found to be a better indicator of the desired physical properties than Brinell hardness.

(2) Incomplete quenching of light metal alloys often results in the development of soft zones. Occasionally this same type of flaw



*To convert to % I.A.C.S., multiply by 1.7241

FIGURE 70. RELATIONSHIP BETWEEN CONDUCTIVITY AND HARDNESS IN COLD AGE-HARDENED ALLOYS

FIGURE 71. TYPICAL TRACES FOR HEAT-STRESSED STEELS

occurs at the end of extruded sections. If a rapid scanning of the specimen surface is made with a probe coil to determine the variation in conductivity, the softer zones may be readily detected and steps taken to correct the process. It is obvious that it is easier to scan a complex shape with a probe coil than to measure hardness by conventional methods.

57. TESTS FOR HEAT TREATMENT

a. Ferromagnetic Materials.

(1) In the general sense, heat treatment may be defined as an operation or combination of operations involving the heating and cooling of a metal or alloy in the solid state for the purpose of obtaining certain desirable conditions or properties. The usefulness of steel is due largely to the relative ease with which its properties may be altered by properly controlling the manner in which it is heated and cooled. The changes which occur in the properties of steel are directly related to changes in the structural make-up of steel.

(2) Annealing tends to increase the saturation flux density in strong fields and has the same effect on the incremental permeability. There is sometimes a reduction in the value of resistivity. Effects given by the different types of steels were shown in figure 57, the main difference being the number of subsidiary peaks which appear with the annealed specimens; this difference becomes particularly noticeable when the high carbon specimens are compared. With steels of high silicon or manganese content, an enlarging of the loops on the trace is apparent even when the sensitivity of the test instrument has been considerably reduced.

(3) Hardening appears to have one very striking effect on the trace, the appearance of a pronounced angularity, making these patterns noticeably different from those of annealed specimens. Figure 71 shows a typical set of traces for the same steel under different conditions of heat treatment. The effect given by the presence of internal strains is unmistakable.

(4) Much more work has to be done to correlate the various complicated traces with the metallurgical structure so that meanings can be attached to small pattern peculiarities.

b. Nonferromagnetic Materials.

(1) The age-hardening of copper alloys has become increasingly important in recent years in the search for materials having improved tensile and heat-resistant properties, combined with as high an electrical conductivity as possible. Since all these alloys are subjected to more complex heat treatments than

normal copper alloys, the control of their properties is more important and less easily accomplished. However, it is generally known that during age-hardening, the hardness and conductivity of the alloys vary. Consequently, the degree of age-hardening attained can be checked not only by a hardness test, but also, more readily, by measurement of the electrical conductivity.

(2) An excellent example of this is afforded by the copper-chromiun age-hardening alloy containing approximately 1% chromium. Tl properties of this alloy can be modified as shown in table VIII, by suitable solution-treatment and ageing. As can be seen from table VIII, the entering of the chromium into solid solution in the copper causes a marked decrease in electrical conductivity which reaches a minimum of approximately 38 %IACS. This relationship, therefore, affords an important means of scientific control, since it is impossible to produce an alloy with optimum properties during the final ageing process if the solution-treatment is incorrect. By rapidly checking the components for conductivity after the solution treatment, the success of the age-hardening process can be gauged.

Table VIII. PROPERTIES OF COPPER - 1% CHROMIUM ALLOY IN VARIOUS CONDITIONS

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

(3) The ageing treatment consists of heating the quenched components to a suitable temperature between 752°F (400°C) and 1112°F (600°C) to precipitate most of the chromium from solution. Figure 72 shows the relationship between the hardness and conductivity of age-hardened components and their dependence on the ageing temperature. By checking the conductivity and referring it to this curve, the success of the

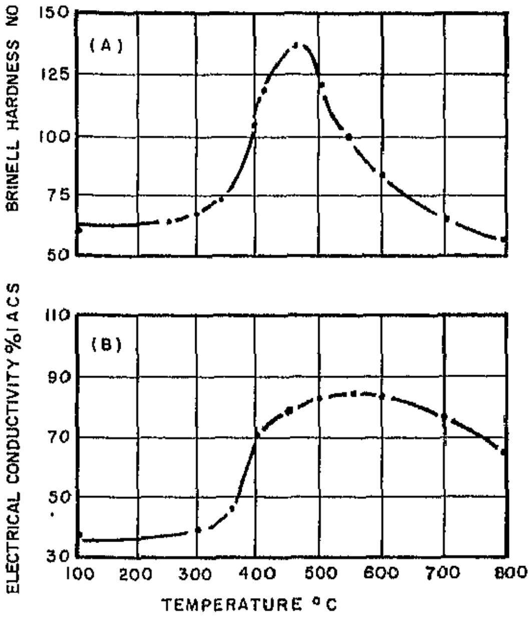


FIGURE 72. VARIATION OF (a) HARDNESS AND (b) CONDUCTIVITY WITH AGEING TEMPERATURE FOR A COPPER-1% CHROMIUM ALLOY

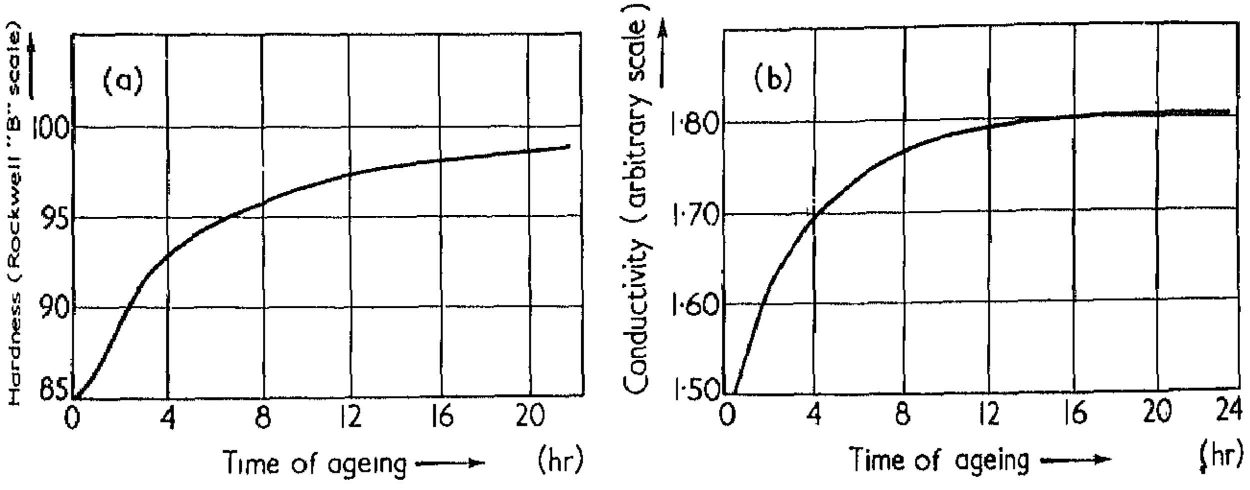


FIGURE 73. HARDNESS AND CONDUCTIVITY OF 7075 ALUMINUM ALLOYS AS A FUNCTION OF AGEING AT ROOM TEMPERATURE

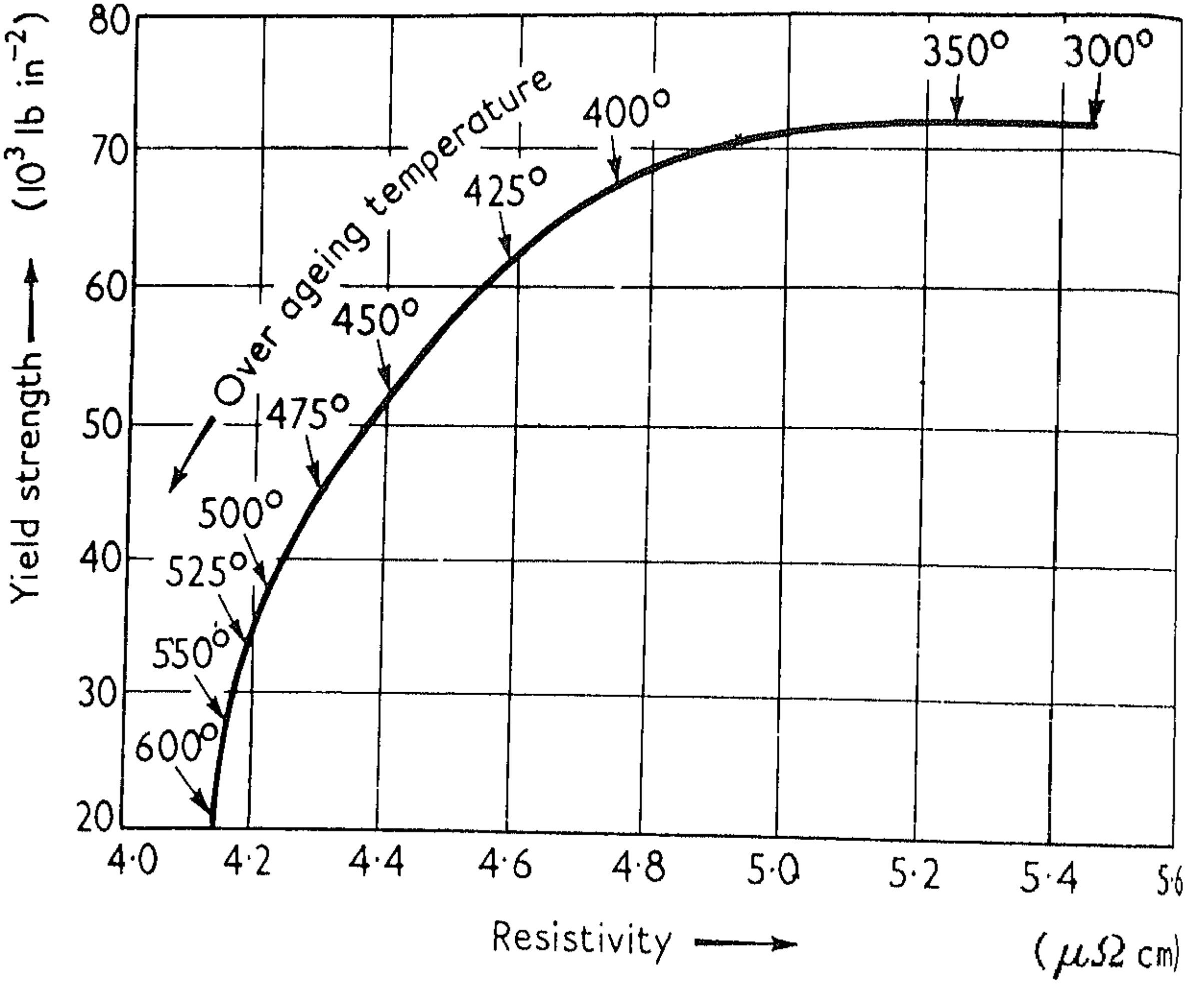


FIGURE 74. YIELD STRENGTH VERSUS ELECTRICAL RESISTIVITY OF 7075-T6 ALUMINUM AS A FUNCTION OF OVER-AGEING
NOTE: The temperature scale used in the figure is Fahrenheit

treatment can be measured very rapidly. In this case, hardness measurements will give equivalent control. Often, however, particularly with large castings or forgings, it is not possible to test the hardness or tensile strength of the actual component and, consequently, determinations are carried out on specially cast test pieces. These determinations can be very misleading, particularly if the component is of very large cross-section; thus, for each application, the measurement of conductivity on a small ground area of the actual piece will provide the most accurate means of control.

(4) Another interesting example of the relationship between a metallurgical property and electrical conductivity is shown in figure 73, which indicates a similarity between the shapes of the curves for conductivity and hardness as a function of ageing time at room temperature for samples of aluminum alloy 7075. An additional relationship is illustrated in figure 74 which shows yield strength of 7075-T6 aluminum alloy samples as a function of electrical resistivity (inverse of electrical conductivity). These samples were overaged for 10 minutes at different temperatures varying from 300°F (149°C) to 600°F (316°C). In both of these illustrations, it can be seen that no unique relationship exists between the electrical conductivity of the 7075 aluminum alloy and its hardness or yield strength. This lack of uniqueness can be shown by referring to figures 73 and 74. Figure 73 shows that after approximately 14 hours of ageing at room temperature, there is relatively little change in either hardness or conductivity with time, so that approximately the same value of either hardness or conductivity will be obtained for values of ageing time greater than 14 hours. In figure 74 it can be seen that there is very little change in yield strength for values of resistivity equal to or greater than 5.0 microhm-centimeter ($\mu\Omega$-cm), so that approximately the same value of yield strength will be obtained for values of resistivity greater than 5.0 microhm-centimeter. These examples do serve to illustrate, however, that in many particular instances in which only one processing variable is varied, the resultant metallurgical property can be indirectly determined, within certain limits, by an eddy current conductivity measurement. There are countless instances in which this sort of relationship is being put to practical use. An example is the checking for overheating of SAE 4340 steel rotors in J-47 turbojet engines. In this application, the rotors are checked at predetermined locations during routine maintenance for the detection of localized overheating of the engine during operation.

58. TESTS FOR CASE DEPTH

a. Ferromagnetic Materials.

(1) The parts of some equipment must have a very hard, wear-resistant surface and also possess great toughness. Such a

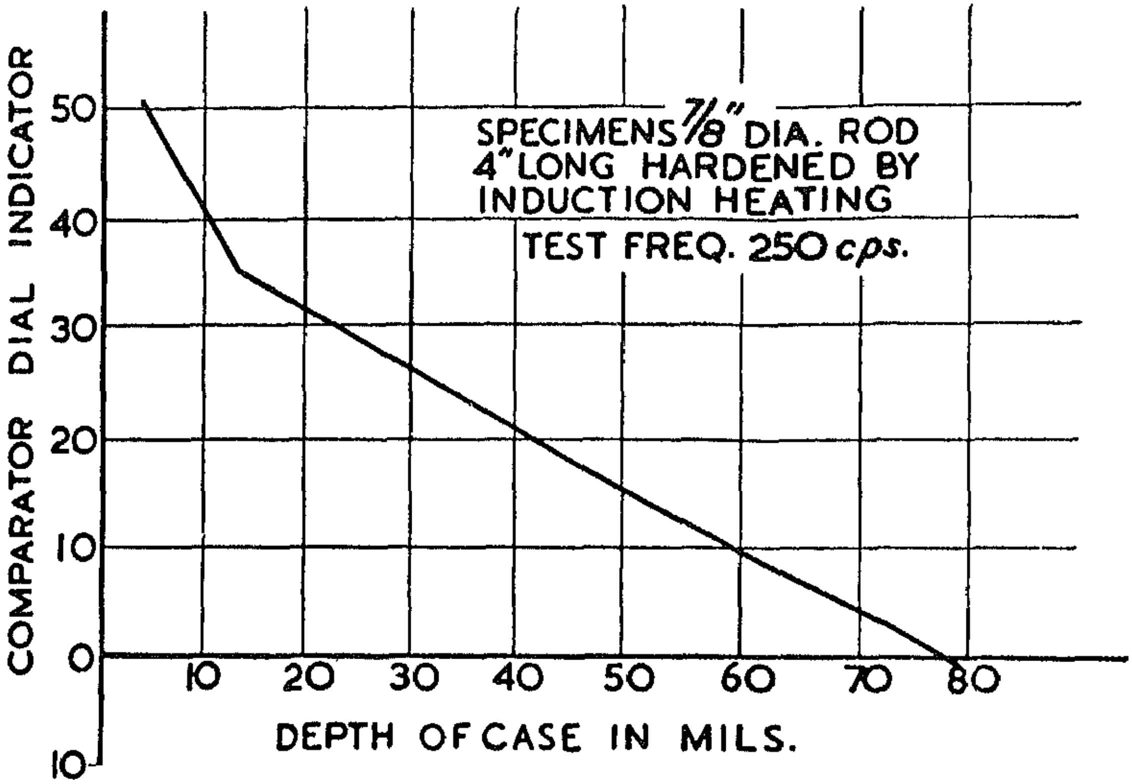


FIGURE 75. TYPICAL COMPARATOR CURVE FOR CASE-DEPTH DETERMINATION

combination is usually not possible in a piece of steel. If the steel is heat-treated to give maximum surface hardness, it is too brittle. If it is treated for maximum toughness, it will not be hard enough. Consequently, several processes, known as casehardening, have been developed by which this combination of properties can be attained. Processes include carburizing, cyaniding, nitriding, and localized surface hardening. The surface hardness obtained by the first two processes (carburizing and cyaniding) depends upon heat-treatment after the composition of the case has been altered. The third process (nitriding) alters the composition of the case in such a way that the compounds formed are inherently hard. The last process, casehardening (surface hardening), depends entirely upon heat-treating the surface of a hardenable steel.

(2) It is sometimes possible to use electromagnetic measurement techniques for the determination of case depth thickness. In normal carburizing techniques, it is not possible to absolutely control the accuracy of the amount of carbon diffusing into the surface layers; during the subsequent heat treatment, it is not possible to accurately control the internal structure of the metal core. For these reasons the magnetic behavior of the specimens is not constant, and at best, only a rough indication of the case depth may be obtained. Comparisons are more easily obtained than definite quantitative figures, but in this case, it is important to sort the material first in regard to core structure. This requirement involves the use of some type of magnetic sorting bridge. A low frequency applied to the coils of the sorting bridg or any other electromagnetic comparator will give good penetration of the core material and allow the segregation of test pieces into groups having like core structures. Use of a higher frequency will then allow sorting according to case depth.

(3) With specimens hardened by high frequency induction or by flam hardening processes, differences in the structure of the core material are not likely to arise and the actual chemical composition of the metal is the same in the case as in the core. However, due to the heat treatment, the metallurgical structure of the case is very much different from that of the base metal, and in addition, there is a great difference in the magnetic and electrical characteristics of the two structures. By using a frequency of 250 cps and standard specimens of known case depths, a typical comparator curve for case-depth determination can be obtained, figure 75, showing almost a straight line relationship between the depth of case and the reading on the comparator indicator.

(4) Much work has been done to develop a satisfactory electromagnetic method of measuring the case thickness in components treated by carburizing, but little success has been obtained.

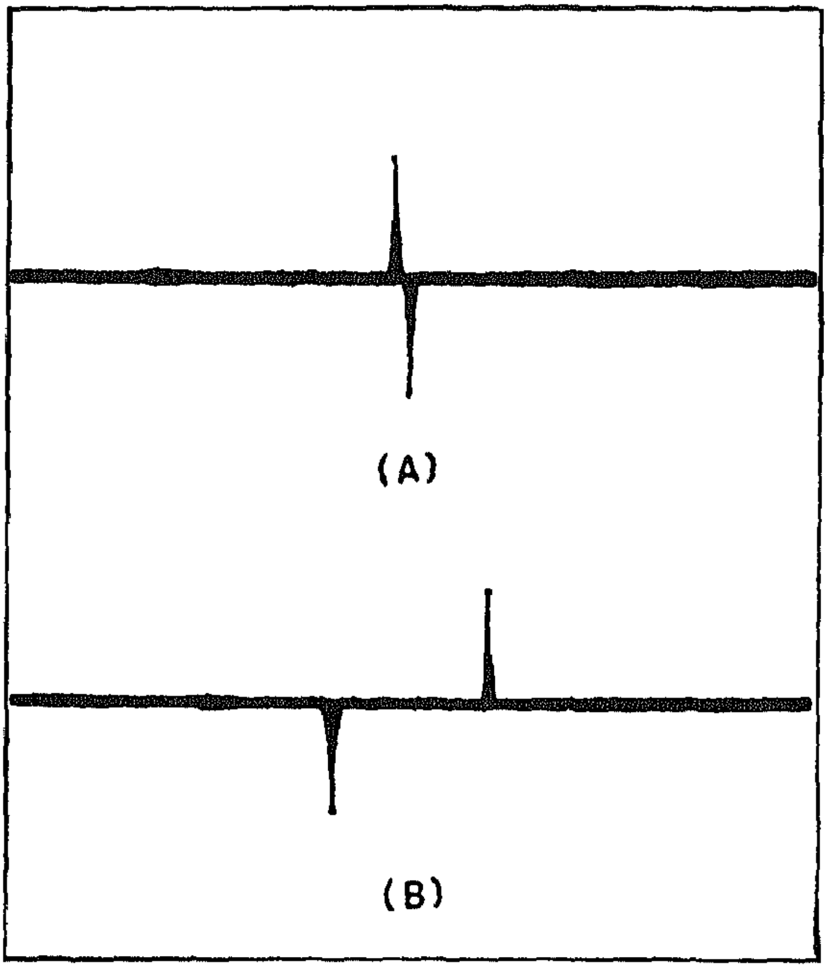


FIGURE 76. PHASE ANGLE BETWEEN FUNDAMENTAL AND THIRD HARMONIC WAS USED TO IDENTIFY SAMPLIES HAVING TOO SOFT A CORE. (A) THE TWO PHASE PULSES ARE MADE TO APPROXIMATELY COINCIDE FOR SATISFACTORILY HARD SAMPLES, (B) SEPARATION OF PULSES INDICATES, IN THIS CASE, THAT THE CORE IS SOFT.

No electromagnetic methods appear to have been devised for the satisfactory measurement of the thickness of the hard surface layer on nitrided steels.

(5) An example of an electromagnetic test involving case depth is given by the following practical application. Among 700,000 case-hardened track pins, there were some whose core hardness did not meet specifications, although the surface hardness was satisfactory. Obviously, it was impossible to segregate the unsatisfactory pins by hardness testing. Satisfactory pins ranged from 32 to 38 Rockwell C hardness in the core; unsatisfactory pins ranged well above and below these limits. Applying harmonic analysis techniques, the relationship of phase angle between the voltage amplitude of the fundamental and the third harmonic was used to identify samples having too soft a core. The two phase pulses are initially made to approximately coincide for satisfactorily hard samples, curve (A) of figure 76. Separation of the pulses indicates, in this case, that the core is soft, curve (B) of figure 76. The differences in phase angle between acceptable and unacceptable samples for this application were more evident than differences in harmonic amplitudes.

b. Nonferromagnetic Materials.

(1) An application relating conductivity measurements to surface tempering occurred in a foundry which cast large chromium-copper electrical contactors. Conductivity values of 85 %IACS were found in the case surface. After grinding approximately 0.030 to 0.040 inch from this surface, the conductivity dropped to 40 %IACS, and varied between 40 and 60 %IACS over this ground area. This reduction and drastic change in conductivity posed a problem, and a series of tests were conducted to explain these mysterious results.

(2) A section of the contactor was etched and a photomicrograph made. Two significant facts were evident. First, an apparent skin of approximately 0.010 inches or greater was detected on the as-cast surface. This finding indicated that the piece was heat treated at the surface only, resulting in high conductivity within the skin and lower values at a greater depth. The sample also had extremely large grains, some 0.50 inches in length. The large grains accounted for the inconsistency in conductivity measurements made on the ground surface, because the individual copper crystals not only exhibited directional properties of conductivity, but also tended to have different absolute values. It was possible to detect the grain boundaries by scanning the surface with a probe coil.

(3) The contactor sample was tempered at approximately 950°F (510°C) for 2-1/2 hours. Table IX illustrates the results

achieved. As a result of this tempering, the conductivity of the entire sample was raised to the expected value of 83 to 85 %IACS, and the Rockwell hardness also increased. This relationship between the tempering process and conductivity indicates that a much higher average value of conductivity could be obtained throughout the entire casting by correct precipitation treatment. It is evident that conductivity measurements can be used to determine the optimum heat treatment conditions and to enable a foundry to maintain closer control over experimental and production castings.

Table IX. TEST INSTRUMENT DATA

Condition	Conductivity of "As-Cast" Surface	Ground Surface	
		Conductivity	Hardness
As Received	85 %IACS	45 %IACS	27 R_B
As Tempered	85 %IACS	83 %IACS	53 R_B

Section III. TESTS FOR DISCONTINUITIES AND INHOMOGENEITIES ACCORDING TO SPECIMEN GEOMETRY

59. GENERAL

a. This section is concerned with the detection and evaluation of surface and internal discontinuities and other conditions relating to quality. A large number of different techniques are in use in electromagnetic testing involving special sensing coil systems and data processing circuitry which depend upon the particular shape of the part to be inspected, or some other property peculiar to the part, for their successful utilization. Generalizations regarding these many techniques are unwarranted and in many instances are very misleading. There are, however, several underlying factors which are common to most of the techniques, and these will be discussed briefly in the following paragraphs.

b. In evaluating an inspection problem, certain philosophies behind the inspection requirements must be considered. One consideration involves an inexpensive item produced in large quantities, while the other is concerned with expensive items produced in smaller quantities. To inspect large quantities of inexpensive items, it is sufficient to screen out all defective material although in doing so, some good material may also be rejected. Where the item is expensive and produced in smaller quantities, it is desirable to analyze the nature of the flaw to reduce the number of rejects to a minimum.

c. When alternating current test methods are used on ferromagnetic materials, it is sometimes difficult to distinguish between the effects of real material defects and those effects due to permeability variations directly or indirectly by structural or stress variations. This is because electromagnetic flaw detectors generally tend to respond more to permeability variations than they do to defects. Most of the false indications given by permeability effects can be neutralized if the component being tested is magnetized to well beyond the saturation value by means of a powerful direct current field. When saturation is complete, only variations in conductivity, dimensions, and the presence of discontinuities in the test part will affect the electromagnetic test equipment. In this state, the behavior of magnetic materials is comparable to that of nonmagnetic materials, so that eddy current principles may be used exclusively to explain the modes of flaw detection. As the test part leaves the region of the direct current field, it not only regains its magnetic properties but also retains a certain amount of magnetism. Demagnetizers can be employed, if necessary, to erase this magnetism.

d. Discontinuities may be detected in metal parts if they are situated in such a manner that they locally interrupt the flow of induced eddy currents in sufficient quantity to alter appreciably the impedance of the electromagnetic test coil. A very narrow discontinuity which lies in a plane parallel to the direction of the eddy current flow will not be detectable, since it will not appreciably alter the flow of current. For example, a radial crack in a tube being inspected with an encircling coil would be detectable, since it would interrupt the induced currents circulating around the tube wall; however, a discontinuity lying in a plane parallel to the principal surface of the tube would not be detectable. A gross lamination in which considerable separation occurs in the metal would, of course, be detectable.

e. The density of the induced currents in a metal part decreases as a function of depth below the surface of the part. The exact nature and severity of the attenuation with depth is a function of the conductivity and permeability of the part, the frequency of the exciting current, and the configuration of both the part and the coil system. Thus, identical discontinuities at different depths below the surface will produce impedance changes in the coil which are not identical; the signal produced by a discontinuity of given size will decrease as a function of depth below the metal surface. This phenomenon seriously hampers efforts to produce quantitative eddy current test results. In addition, it is quite possible that the conditions which produce the discontinuity also produce changes in the permeability or conductivity of the metal adjacent to the discontinuity, which further hampers attempts to produce quantitative results.

f. Another factor which must be considered in the detection and evaluation of discontinuities, is the separation of signals produced by discontinuities from signals produced by the large number of other variables in the inspection system. Since the exact nature of the signals which are obtained, and therefore their interpretation, depends entirely upon the configuration of the part and the type of coil system employed, no further generalizations can be made. The remainder of this chapter will be concerned with the inspection of tubes, rod, wire, sheet, plate, the measurement of thickness, and the inspection of end items.

60. INSPECTION OF TUBES, ROD AND WIRE

a. The inspection of tubing is particularly important in view of the severe fabrication processes frequently employed, and the high duty service required from tubular structures. A very large proportion of commercial tubing is formed by seam welding, a process likely to introduce a number of defects if not done correctly. As these weld defects can lie along the whole length of the tube, a 100 percent inspection is frequently required. Seamless drawn tubing, produced either by piercing or extrusion, may contain surface defects due to the ingot condition or the piercing or extrusion processes. The ingot defects retained by the tube take the form of elongated flaws or seams which are very difficult to detect by normal visual methods.

b. As many of the forming operations involve expanding the tubes, the presence of any elongated nonmetallic stringers is particularly undesirable as they are likely to give rise to serious splits during the expanding operation. The stringers usually occupy only an extremely small portion of the metal cross-sectional area and this considerably increases the difficulties associated with their detection.

c. For the satisfactory inspection of tubes, rod and wire, the following essential requirements must be satisfied:

(1) The test must be absolutely nondestructive.

(2) The test must be rapid and reliable.

(3) The position of defects must be indicated to assist in the salvage of sound material.

(4) The test should not require the material to be formed in any special way.

(5) No special cleaning methods should be necessary.

(6) When possible, the testing should be automatic.

d. Among the factors interfering with satisfactory inspection operation e the following:

(1) The minute size of serious defects.

(2) Slight variations in wall thickness, allowed in the specifications, are sufficient to mask indications given by defects.

(3) Slight eccentricity of the tube walls.

be lengths.

(5) Variations in the composition and magnetic and electrical properties of individual tubes.

e. At their present stage of development, electromagnetic techniques can, if properly utilized, be used to perform valuable inspection on small diameter tubing or pipe. For the detection of gross defects in commercial grade tubing or pipe, the encircling coil technique is the fastest and most effective nondestructive test which exists today. The inspection of premium quality tubing or pipe for critical applications by this method allows:

(1) High speed detection of intergranular corrosion on the inside surface.

(2) The detection of foreign metal pickup on the inside surface.

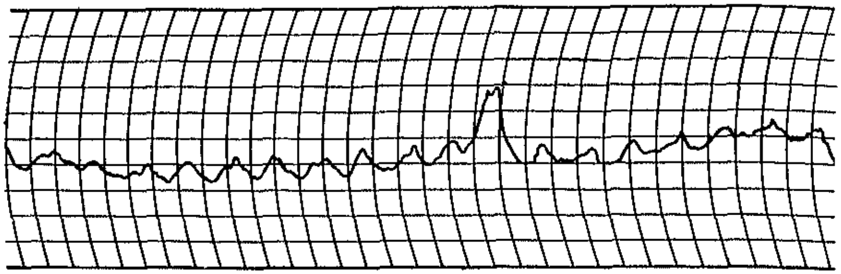
(3) High speed continuous gaging of dimensions of the tubing or pipe.

(4) High speed detection of defects.

f. Intergranular attack on the inner surface of tubing produces signals similar to the indications illustrated in figure 77 which appear less sharp than signals caused by cracks. The indicated signal was produced by the 0.002 inch deep, corrosive condition shown in the photomicrograph. The smaller signals appearing on the trace were produced by dimensional variations and less severe conditions of intergranular attack.

g. Foreign metallic particles are sometimes found embedded in the inside wall of redrawn small diameter tubing or pipe. These bodies are usually picked up from tools used in the manufacturing of the tubing or pipe and generally have a high magnetic permeability; hence, they are very easily detected by eddy currents in a nonferromagnetic tube or pipe. Figure 78 shows a photomicrograph of two such pickup areas on the inside wall of an Inconel tube and the corresponding eddy current trace. The tube has a nominal outside diameter of 0.188 inches and a wall thickness of 0.025 inches. The defective areas are indicated by the two sharp negative spikes on the trace. The smooth cyclic variations in this trace are due to dimensional variations in the tube.

h. The ability of an electromagnetic test system to distinguish between diameter and wall-thickness variations is illustrated in figure 79. The signal traces are recordings from the two signal channels, reactive and resistive components respectively, for two 35-inch lengths of Inconel tubing (0.229 inch outside diameter; 0.025 inch wall thickness) which were previously stretched to accentuate their dimensional variation. Above the traces are shown plots of the average wall thickness as measured with the ultrasonic resonance thickness gauge. Plots of the average outside diameter, as measured with mechanical micrometers, are shown below the traces. It is readily seen that a close correlation exists between the instrument signal and the other independent measurements. The electromagnetic gauging was accomplished at a linear tube speed of approximately 1 foot per second and at an operating frequency of 189 kilocycles per second.



INSTRUMENTATION: CYCLOGRAPH TYPE WITH ENCIRCLING COIL
FREQUENCY: 78 kc
TUBING: $\frac{1}{2}$- x 0.0625-in NIMONIC

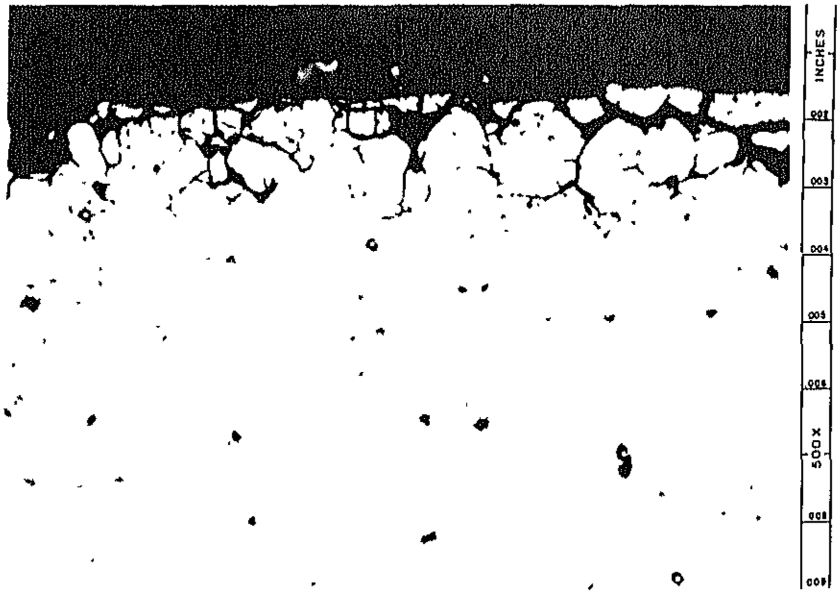


FIGURE 77. EDDY CURRENT SIGNAL TRACE AND PHOTOMICROGRAPH OF INTERGRANULAR CORROSION ON INSIDE SURFACE OF NIMONIC TUBING

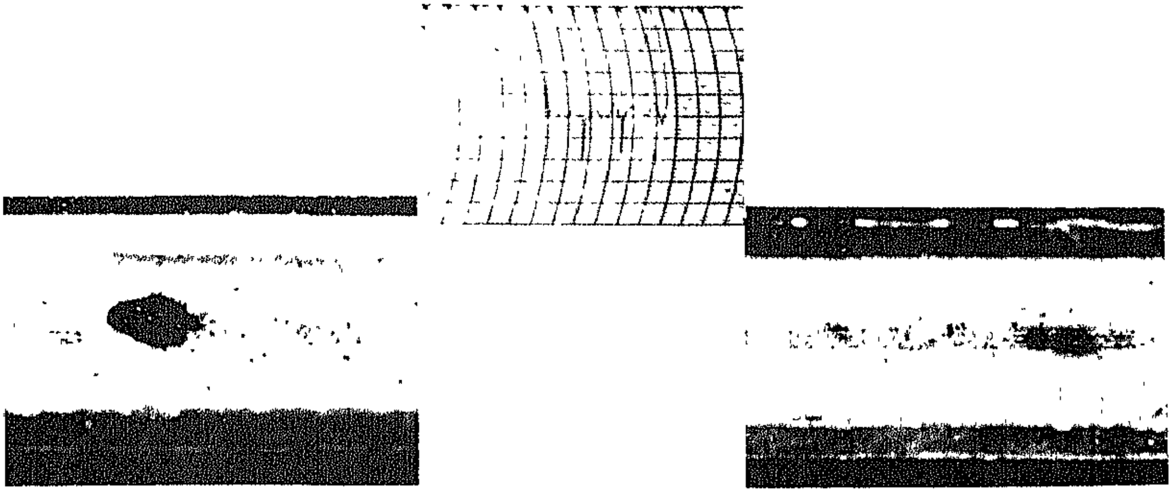


FIGURE 78. EDDY CURRENT SIGNAL TRACE AND PHOTOMICROGRAPH OF DEFECTIVE ICONEL TUBING OF 0.188 INCH NOMINAL OUTSIDE DIAMETER WITH A WALL THICKNESS OF 0.025 INCHES

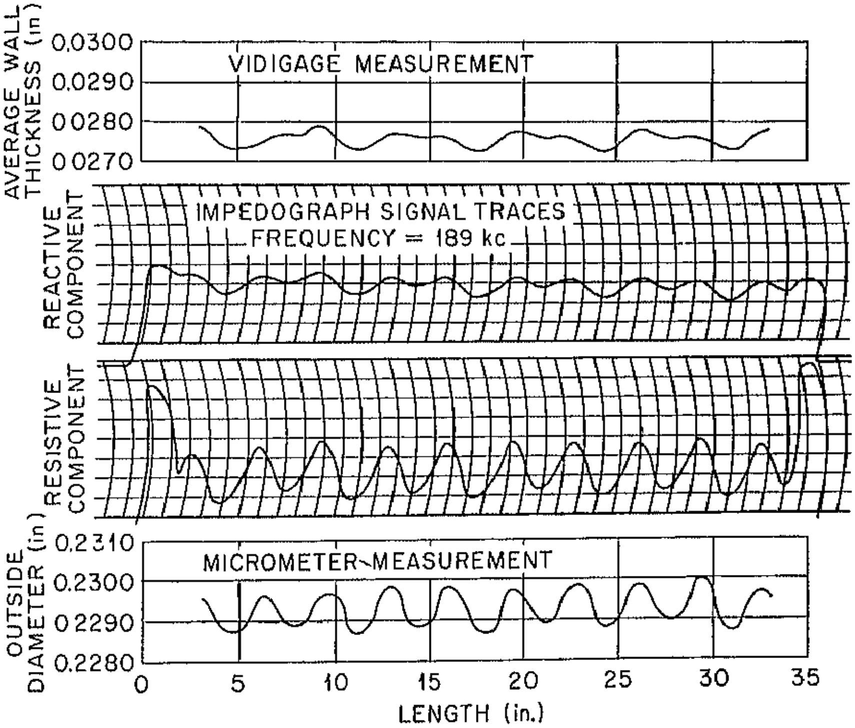


FIGURE 79. COMPARISON OF RESISTIVE AND REACTIVE COMPONENT SIGNAL TRACES WITH ACTUAL DIMENSIONAL VARIATIONS IN AN INCONEL TUBE OF 0.229 INCH NOMINAL OUTSIDE DIAMETER WITH A WALL THICKNESS OF 0.025 INCHES

i. Eddy current techniques have been effectively used in electric weld mills supplying 0.25 to 2.50 inch OD steel tubing for either mechanical or pressure applications. Leakers and certain defects in the weld zone that may result in breaks during forming or fitting processes are most critical for pressure applications; whereas, poor welds, surface finish affecting plating, and those defects that may cause structural failure are most important considerations in mechanical tubing applications. Classes of defects which have been detected in electric weld steel tubing are illustrated in figure 80.

j. The examination of steel bar stock is also of particular importance. For example, when using lathes with automatic controls for machining bar stock, it is essential that the starting material be free from flaws. Obviously, it would be not only senseless but very costly to complete the machining of a piece of metal and then find out is was worthless. The most common flaws in bars or rods result either from heat treatment or from ingot defects, and consist of seams, surface and subsurface cracks, slivers, segregations, hard spots, surface scabs, and voids. Figure 81 shows: (a) a seam and a crack in a high quality alloy steel bar, and (b) a serious subsurface crack in a plain carbon steel bar. These defects are readily detected by electromagnetic test equipment.

k. An automatic eddy current inspection system for locating defects that would affect the end use quality and reliability of tubing or pipe is pictured in figure 82. The system combines electronic and mechanical equipment. Pipe or tubing is fed through an eddy current sensing coil by means of a heavy-duty, mill service feeder that restricts the transverse motion of the fast-moving pipe or tubing to 0.050 inch or less in any direction from true center. This rigid control is necessary to prevent false signals as the pipe passes through the inspection coils. As the electromagnetic instrumentation senses a defect, a signal is created which triggers one or more readout methods such as a time delay and paint spray, oscilloscope, pen recorder, flashing light, or audible alarm. Setup and alibration of the detection system is simple and straightforward. Howver, calibration is required each time the sensing coil is changed for a ifferent pipe or tubing size. For calibration, a sample containing a reresentative artificial defect is passed through the coil several times and he equipment adjusted to detect it. Generally, maximum mill speeds can e achieved, depending upon the sensitivity level desired. This sensitivity evel is variable and can be controlled. Three to six inches of the ends of ach length of pipe or tubing will respond as defects to the sensing coil. o suppress this end-effect, a circuit is usually added to avoid triggering he readout systems.

l. Springs of improved quality result from wire that has been inspected ith electromagentic flaw-detection equipment such as that shown in figre 83a. The mechanical handling features of the test equipment permit the lectronic system to detect harmful flaws at production speeds as shown in igure 84b. The electronic system provides a permanent paper chart ecord for each bundle of wire showing any questionable sections. These

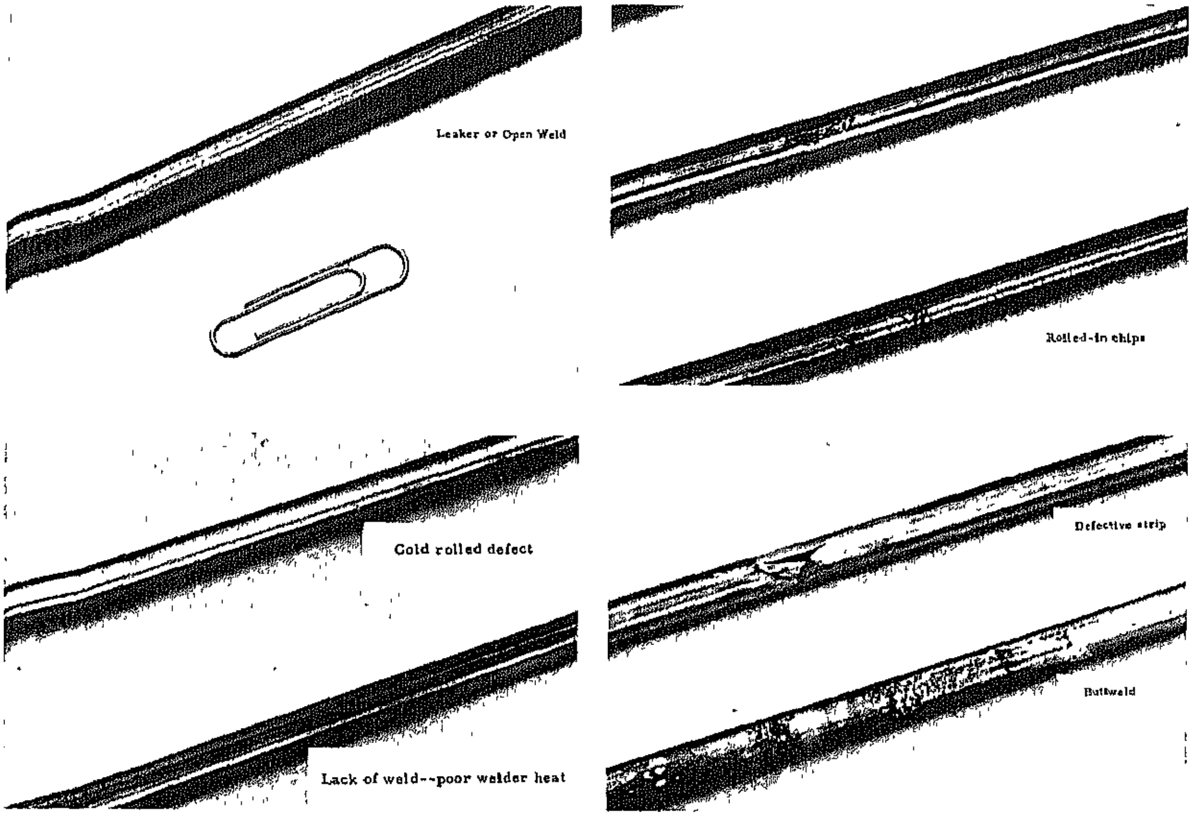


FIGURE 80. CLASSES OF DEFECTS WHICH HAVE BEEN DETECTED IN ELECTRIC WELD STEEL TUBING

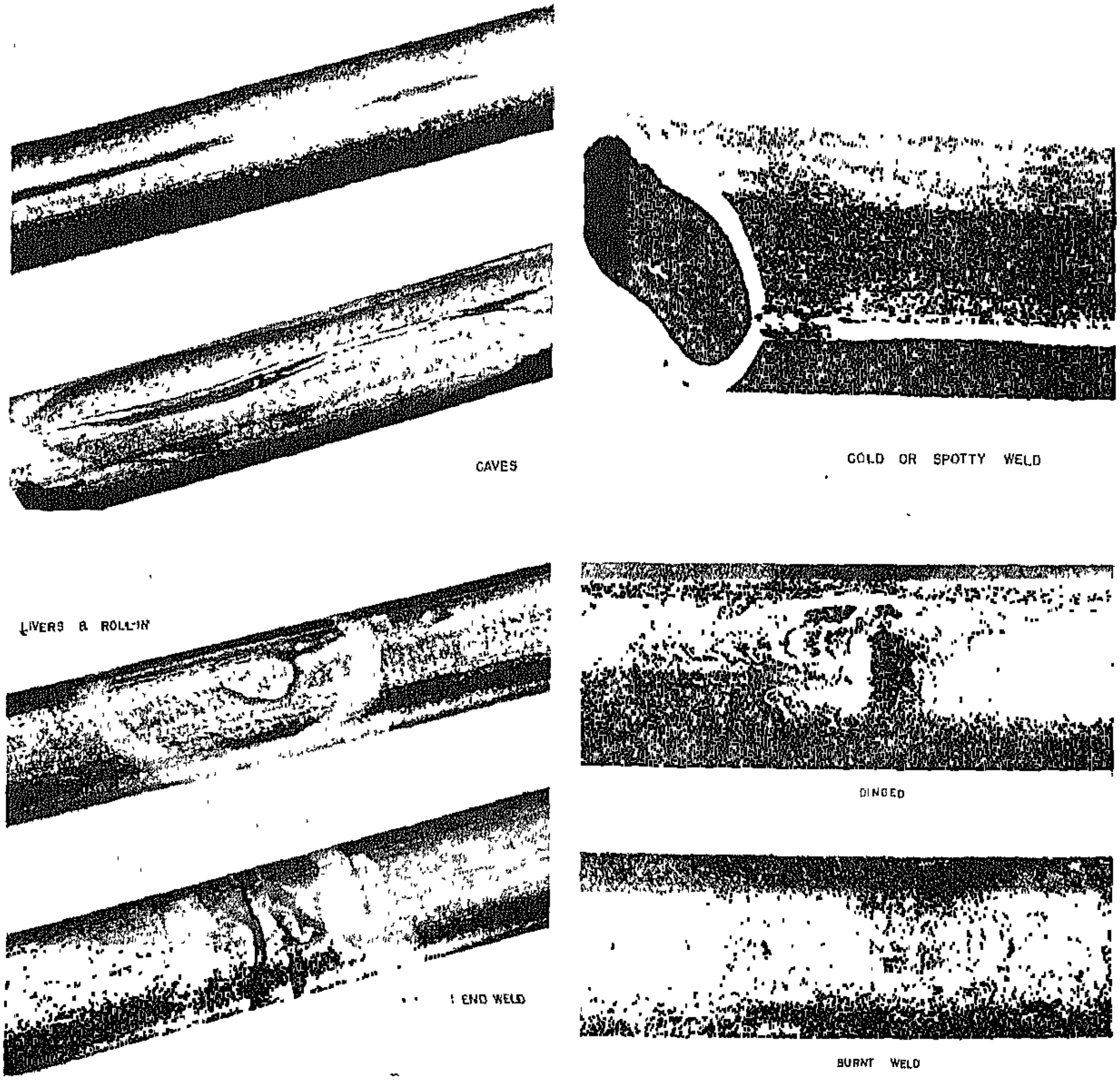
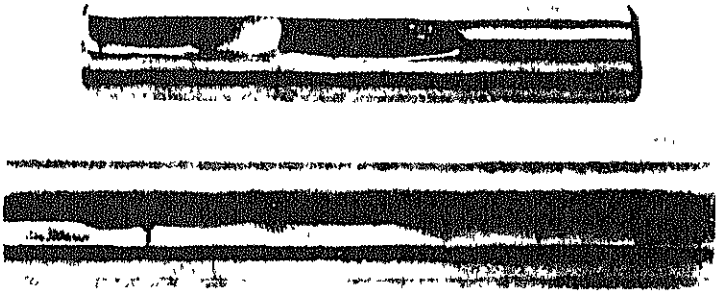
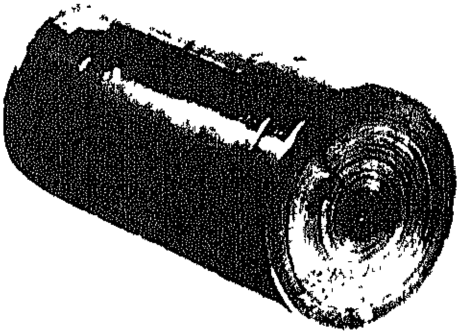


FIGURE 80 (Cont). CLASSES OF DEFECTS WHICH HAVE BEEN DETECTED IN ELECTRIC WELD STEEL TUBING



(a). A seam and a crack in a high quality alloy steel bar



(b). A serious subsurface crack in a plain carbon steel bar

FIGURE 81. DEFECTS IN HIGH QUALITY ALLOY STEEL BARS

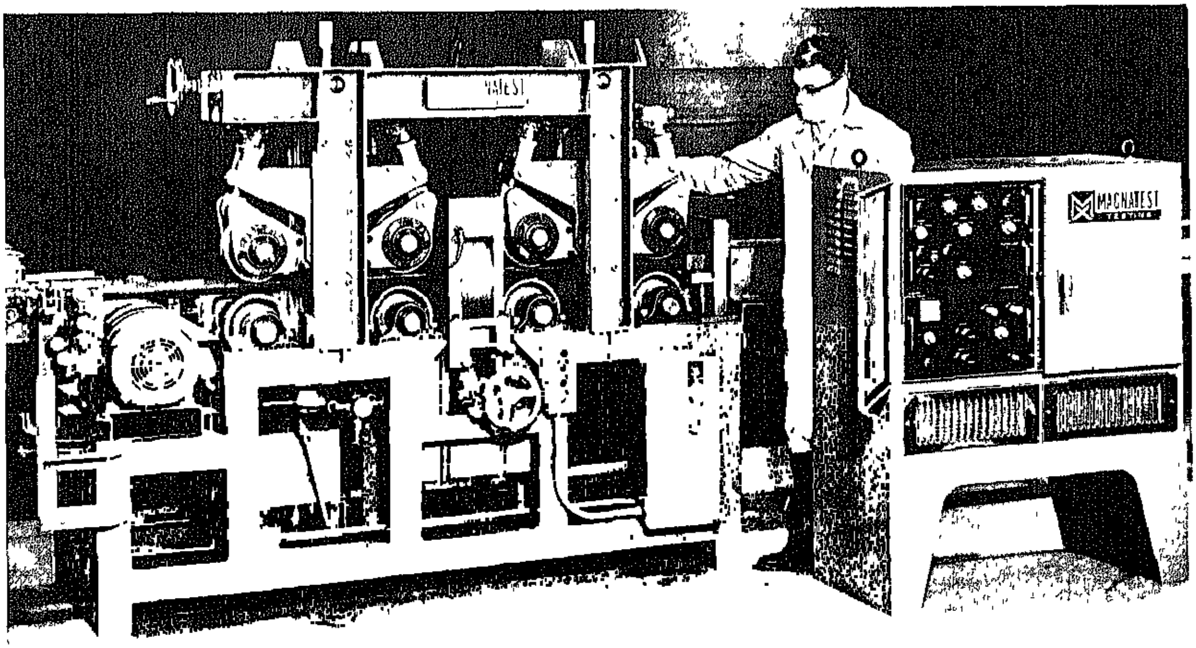
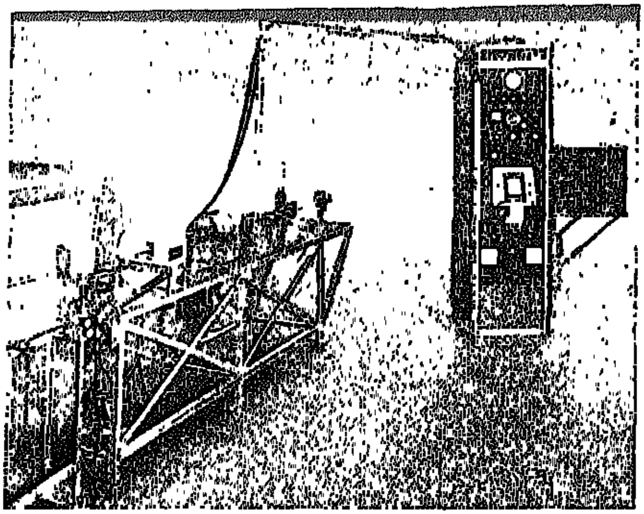
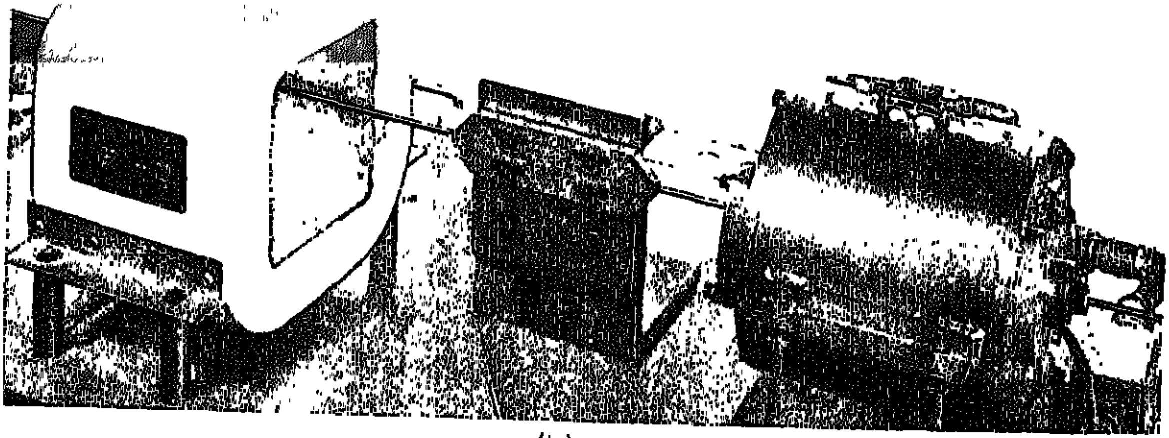


FIGURE 82. AN AUTOMATIC EDDY CURRENT INSPECTION SYSTEM



(a).

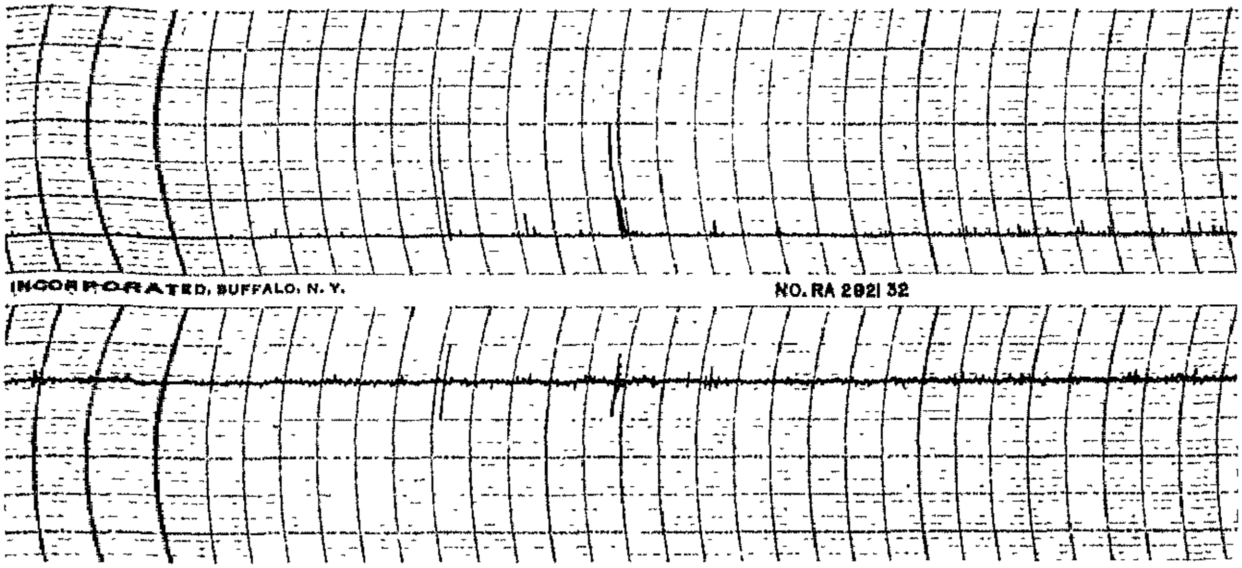
Springs of improved quality result from wire that has been inspected on this eddy-current flaw-detectiomequipment. Electronic control panel at right prints a paper-tape record that indicates harmful nicks, seams, or scratches in the wire. Spray gun at left marks location of flaws in the wire.



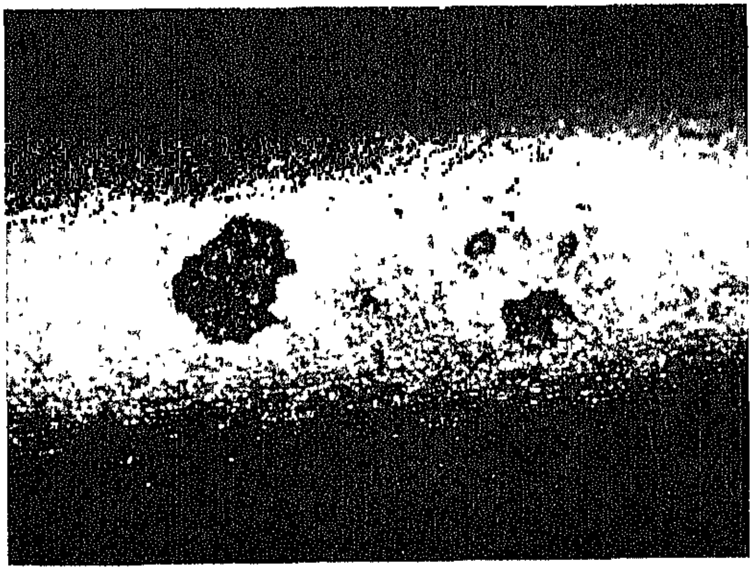
(b).

/ire traveling at production speeds passes through a pair of sensing oils in the housing at right. Tunnel-like structure at left is demagnetizer.

FIGURE 83. EDDY-CURRENT FLAW-DETECTION EQUIPMENT

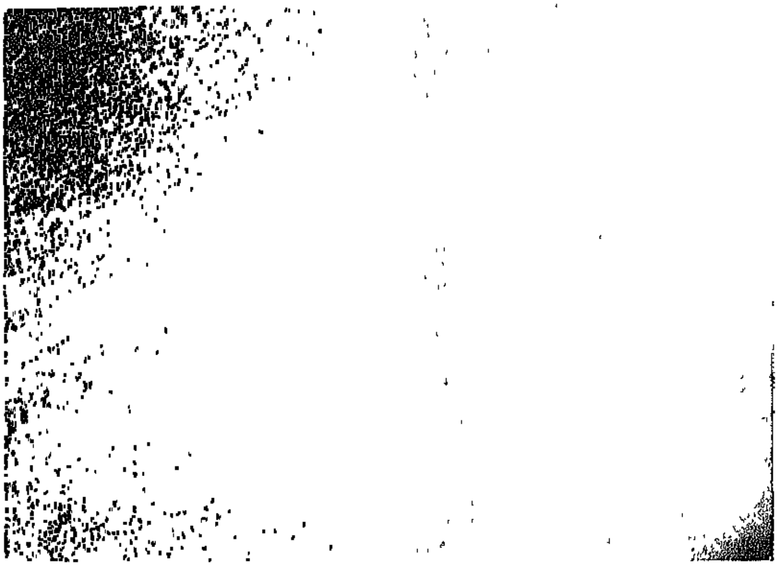


(a). Portion of typical tape record of valve-spring wire inspected by automatic flaw-detection equipment. Defect indications are of pits 0.002" -0.003" deep.



(b). Pits wire as located by automatic flaw-detection equipment. (0.187 valve-spring wire, unetched. Magnification - 15X).

FIGURE 84. TRACE AND FLAWS FOUND BY AUTOMATIC FLAW-DETECTION EQUIPMENT



(c). Sliver found by automatic flaw detector. (Magnification - 15X).

(d). Seam 0.003" deep located by automatic flaw-detection system. (0.187 valve-spring wire, unetched. Magnification - 30X).

FIGURE 84 (Cont). TRACE AND FLAWS FOUND BY AUTOMATIC FLAW-DETECTION EQUIPMENT sections are immediately marked by colored lacquer for identification and subsequent rejection if they contain an excessive number of flaws.

m. When testing wire, it should be remembered that commercial tolerances permit slight variations in the diameter, chemical composition, and hardness. These variations could result in test signals indicating defects. To eliminate the effect of these small variations, a differential coil system is utilized. Since minor variations in diameter, chemical composition, hardness, etc., occur gradually along the length of the wire, and as both coils are affected equally, no test signal results. A defect, however, affects first one coil and then the other, changing or unbalancing their output and resulting in a signal which triggers the alarm, and is recorded on a paper chart. By the proper interpretation of the chart, as shown in figure 84a, the nature of the defects in the wire being tested can be determined. Examples of defects which have been detected in wire include pits, slivers, and seams and are illustrated in figures 84b, c, and d, respectively.

61. INSPECTION OF SHEET AND PLATE

a. The three principal areas of inspection of sheet and plate involve tests for material properties, flaw detection, and thickness measurements. An example of the first area is the measurement of the mechanical properties of Armco 17-7 PH steel sheet during stretch-ageing operations. The determination is accomplished by using a relationship between the meter indications of the electromagnetic instrument, used in conjunction with a probe coil, and the previously determined aged mechanical properties of the material. In this example (fig. 85), the die or back-up plate of the press is first chilled to 20°F (-6.7°C), then the sheet is stretched with the test probe in direct contact with it. The stretching is continued until the meter reads in the prescribed range which has been established by trial and error. After stretching, the sheets are pierced, routed, or otherwise made into blanks. After forming, the parts are aged to 850°F (454°C) for one hour. This procedure enables finite control of the process which is aimed at providing sheet properties of 5 percent elongation and 180,000 to 220,000 psi of ultimate tensile strength. Using this electromagnetic technique for sheet acceptance, 92 percent of the acceptance tensile tests have been eliminated resulting in savings of labor, material, and testing cost.

b. Inspection of large size sheet and plate for the location of defects is usually accomplished by scanning the surface area of the material with a probe coil by either manual or mechanical means. Any instrument indications which are obtained must be correlated with the severity of the defects. Acceptance levels associated with instrument indications must be predetermined either by using a standard containing natural or machined defects, or by experience since the test conditions associated with each inspection problem require a unique solution.

c. The remaining area of inspection of thin sheet and plate is the guaging of thickness. This application shall be discussed in paragraph 62.

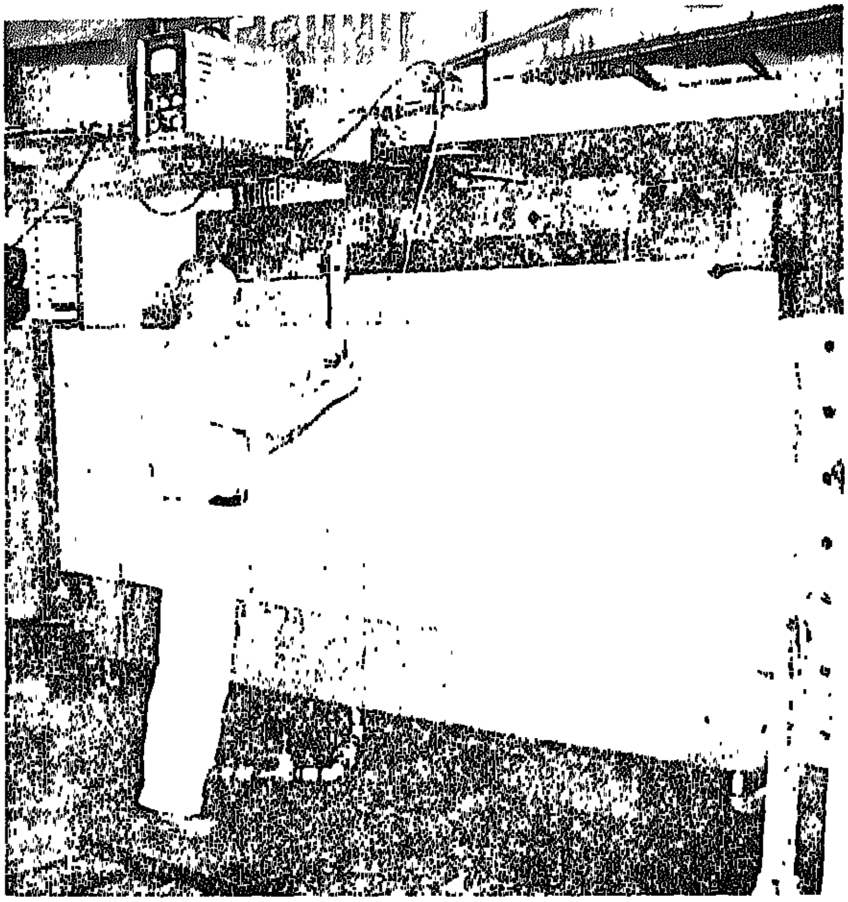


FIGURE 85. OPERATOR PLACING EDDY CURRENT PROBE IN CONTACT WITH A SHEET TO BE STRETCHED. IT IS HOOKED TO THE METER OVERHEAD, AND METER READINGS TELL THE OPERATOR WHEN TO STOP THE STRETCHING OPERATION.

62. MEASUREMENT OF THICKNESS

a. General. The metal industries produce a large number of metal products which are clad or coated with another, usually more expensive, metal to obtain special surface properties such as corrosion resistance, wear resistance, or improved appearance. These coatings are produced by various methods, most important of which are electrodeposition, hot-dipping, cladding, and spraying. For controlling the thickness of the deposit and also for inspection purposes, reliable and rapid methods of measuring the metallic coatings are necessary. There are many methods available including chemical, mechanical, optical, microscopic, magnetic, electromagnetic, X-ray, spectroscopic, and radioactive techniques, each of which has certain particular fields of application, although there is considerable overlapping. The discussion of the measurement of thickness by electromagnetic techniques will include the measurement of coating thickness, the measurement of cladding thickness, and the gauging of sheet and thin plate thickness.

b. Coating Thickness.

(1) Within recent years, electromagnetic techniques have found widespread use in the plating and paint industry for measuring the thickness of coatings. Such applications have utilized eddy currents at particular frequencies to take advantage of the sensitive relationship between conductive coating thickness and the depth of current penetration. Thicknesses of gold, silver, copper, and other metallic platings can be determined up to a few thousandths of an inch to within 2 or 3 percent accuracy. Paint coatings or other insulated coatings on metallic bases have also been measured by eddy currents. For measuring paint thickness, the "gap" or coupling between the test coil and the metal or alloy is used as a measure of the paint coating thickness.

(2) There are four general types of combinations of coatings and base materials which lend themselves to electromagnetic testing. The operating procedure used with the test instrument for a specific combination of materials is governed by each particular case. The classification of combinations of coatings and base materials is as follows:

(a) Metal coating has a higher conductivity than the base metal, for example: copper, zinc, or cadmium on steel, etc.

(b) Metal coating has a lower conductivity than the base metal, for example: chromium on copper, lead on copper, etc.

(c) Non-conductive coatings on a metallic base material, such as anodic film or paint on aluminum, organic coatings on metals, etc.

(d) Metal coatings on a nonconductive base material, such as metallic films on glass, ceramics, plastics, etc.

(3) Eddy currents induced in a metallic surface can be limited to a thin surface layer by using high test frequencies. The thickness of this layer, which is usually referred to as the depth of penetration of the currents, is inversely proportional to the square root of the product of the test frequency, the conductivity, and the permeability of the metal. For example, eddy currents penetrate twice as deep in yellow brass as in silver if the test frequency is held constant, because yellow brass has one quarter the conductivity of silver. Since yellow brass and silver are nonferromagnetic materials and since the permeabilities of all nonferromagnetic materials are essentially equal, the permeability factor cancels out whenever depth of penetration ratios are to be determined for nonferromagnetic materials (see figures 86 to 88). For a given test frequency, the magnitude of the eddy currents induced in a surface layer will depend upon the conductivity of that layer through which the currents flow, other factors being constant. If the coating and the base metal have different conductivities, the effective conductivity of the composite surface layer and hence the magnitude of the induced eddy currents, will depend to a large extent upon the thickness of the coating (fig. 89). The magnitude of the eddy currents is measured indirectly through the effect of its magnetic field which opposes that of the inducing current. Another property, magnetic permeability, is involved when magnetic materials such as steel and nickel are employed. In this case, eddy current depth of penetration is inversely proportional to the square root of the magnetic permeability. In practice, this results in a relatively shallow depth of penetration in magnetic materials.

(4) In practice, no calculations are required for measuring coating thickness, as calibration curves are used which are made of specimens having known coating thicknesses as shown in figure 90. Each combination of metals requires an individual calibration curve. Calibration curves have two limits or end points: one being the reading of the meter with the probe on the bare base metal, the other being the reading with the probe on a thick layer of metal composing the coating, the layer being thicker than the depth of penetration of the eddy currents. Coating thickness may also be measured directly without the use of any calibration curves with a test instrument (fig. 91) utilizing interchangeable, precalibrated meter scales such as the one shown in figure 92.

(5) The range of coating thickness measurements is governed by probe coil design, as well as frequency selection and material combinations. For example, the four measuring probes shown in figure 87b and designated as A, B, C, and D, are used with

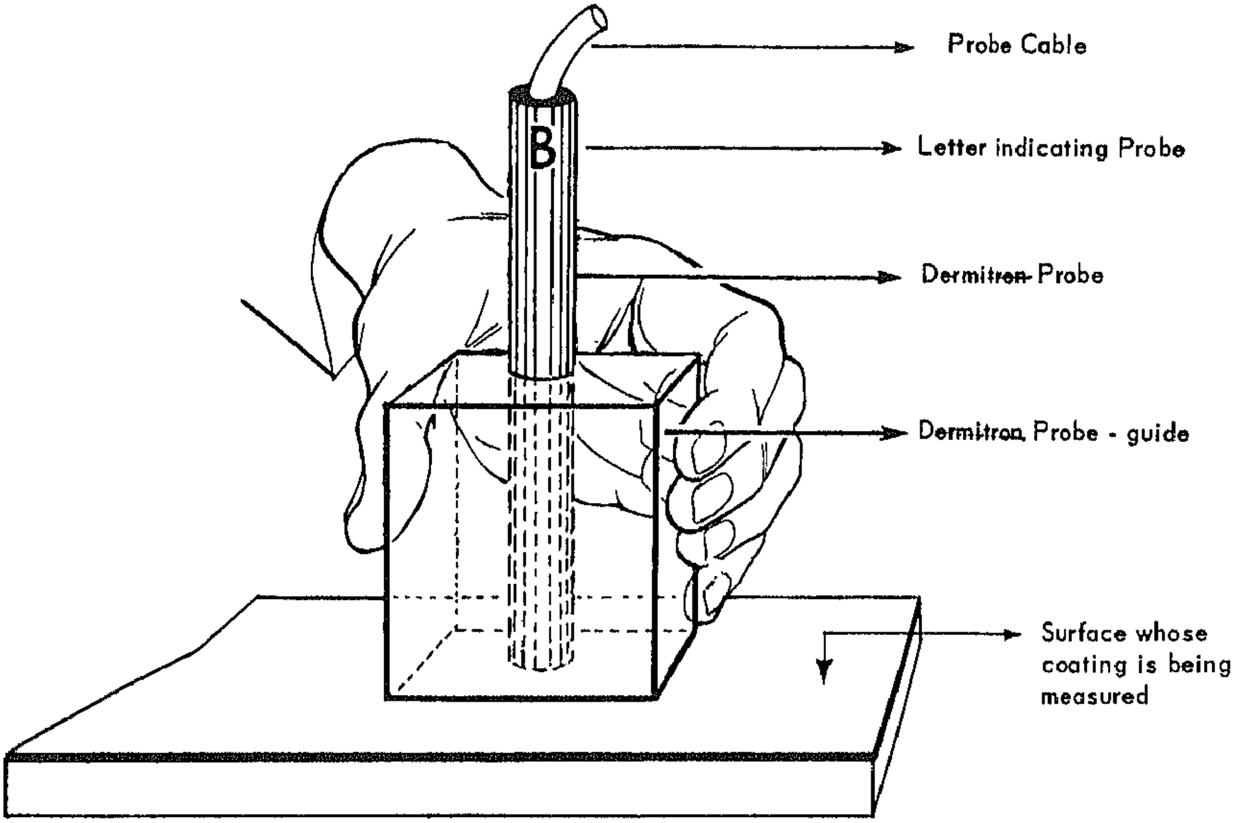
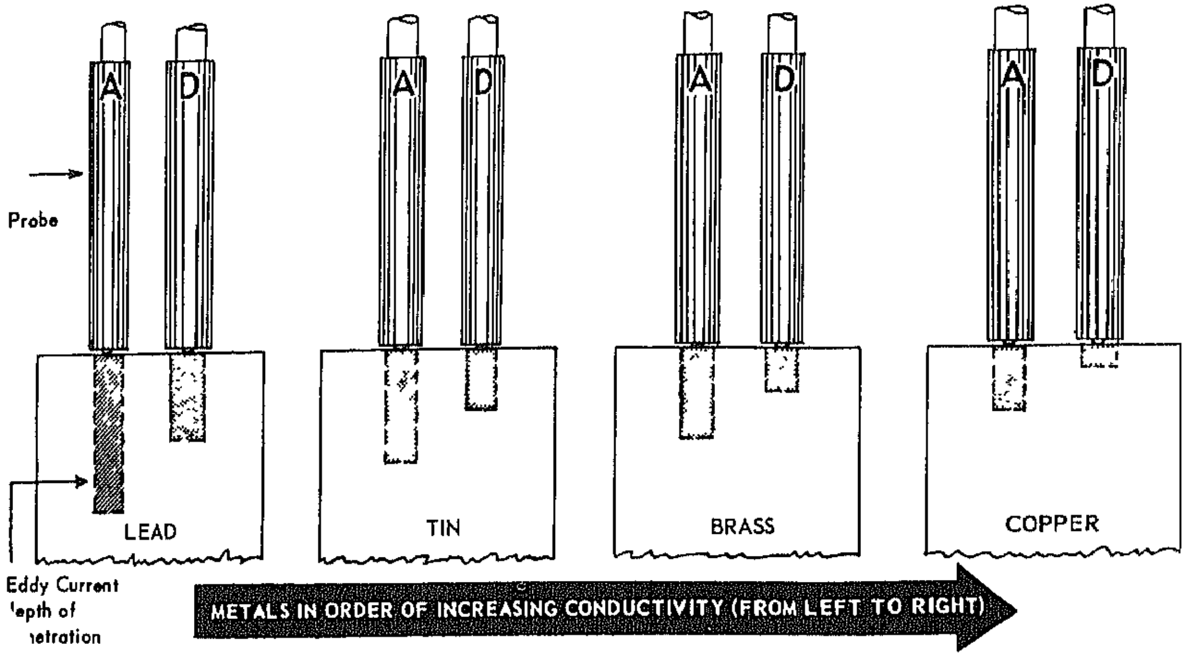
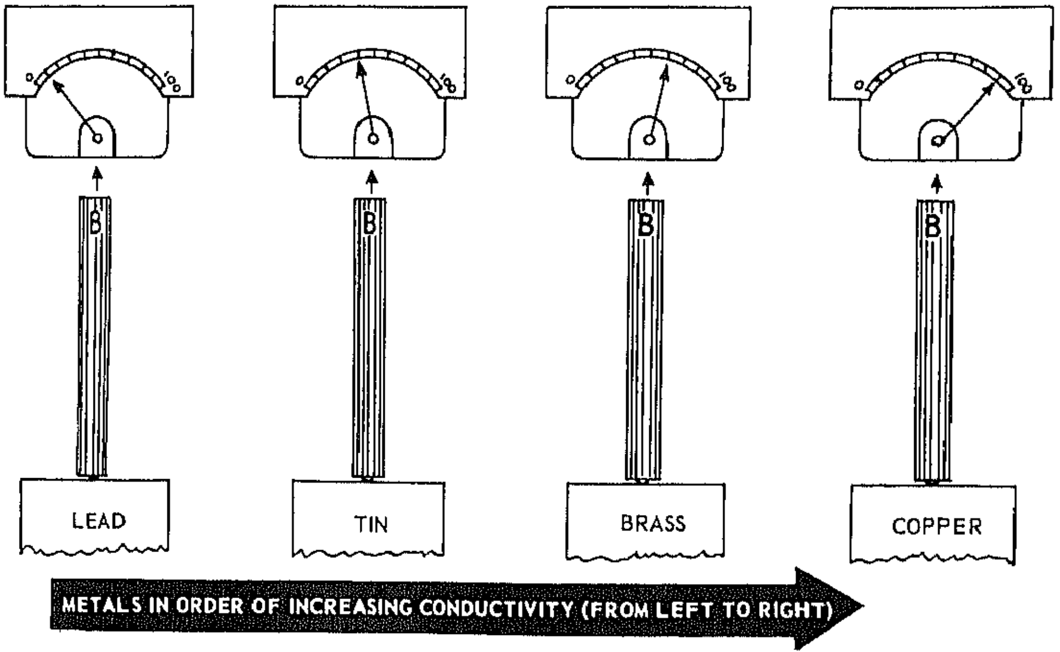


FIGURE 86. DIAGRAM SHOWING PROBE AS APPLIED TO COATINGS BEING MEASURED



a). Depth of eddy-current penetration in various metals using low-frequency probe "A" and high-frequency probe "D" - illustrating that (1) penetration is less in metals of greater conductivity, (2) penetration is greater when using low-frequency probe than when using high-frequency probe.



(b). Relative instrument readings when probe is applied to various metals

FIGURE 87. DEPTH OF EDDY-CURRENT PENETRATION AND RELATIVE INSTRUMENT READINGS IN VARIOUS METALS

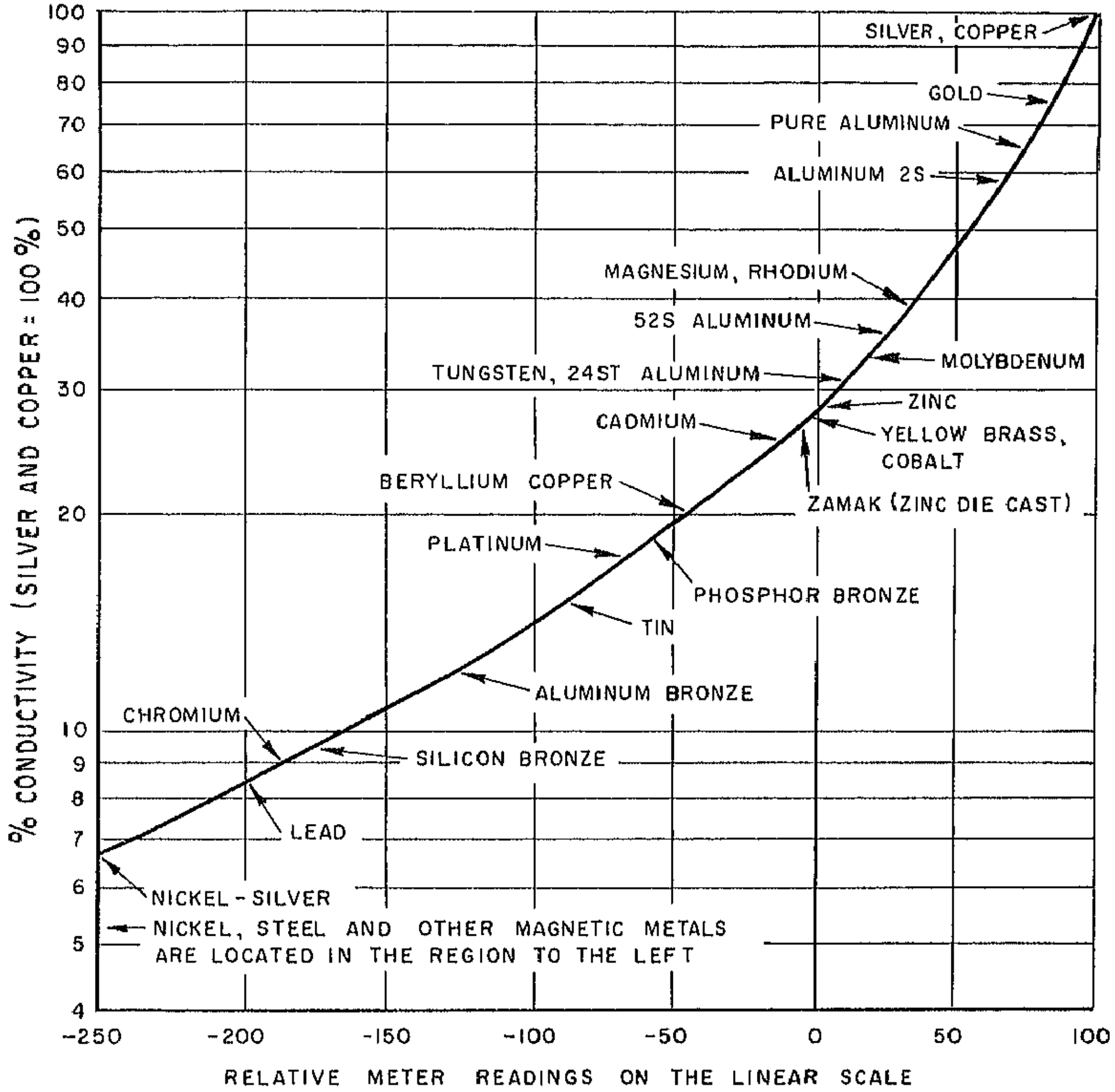


FIGURE 88. RELATIVE CONDUCTIVITY OF METALS AND ALLOYS VERSUS EDDY CURRENT METER READINGS

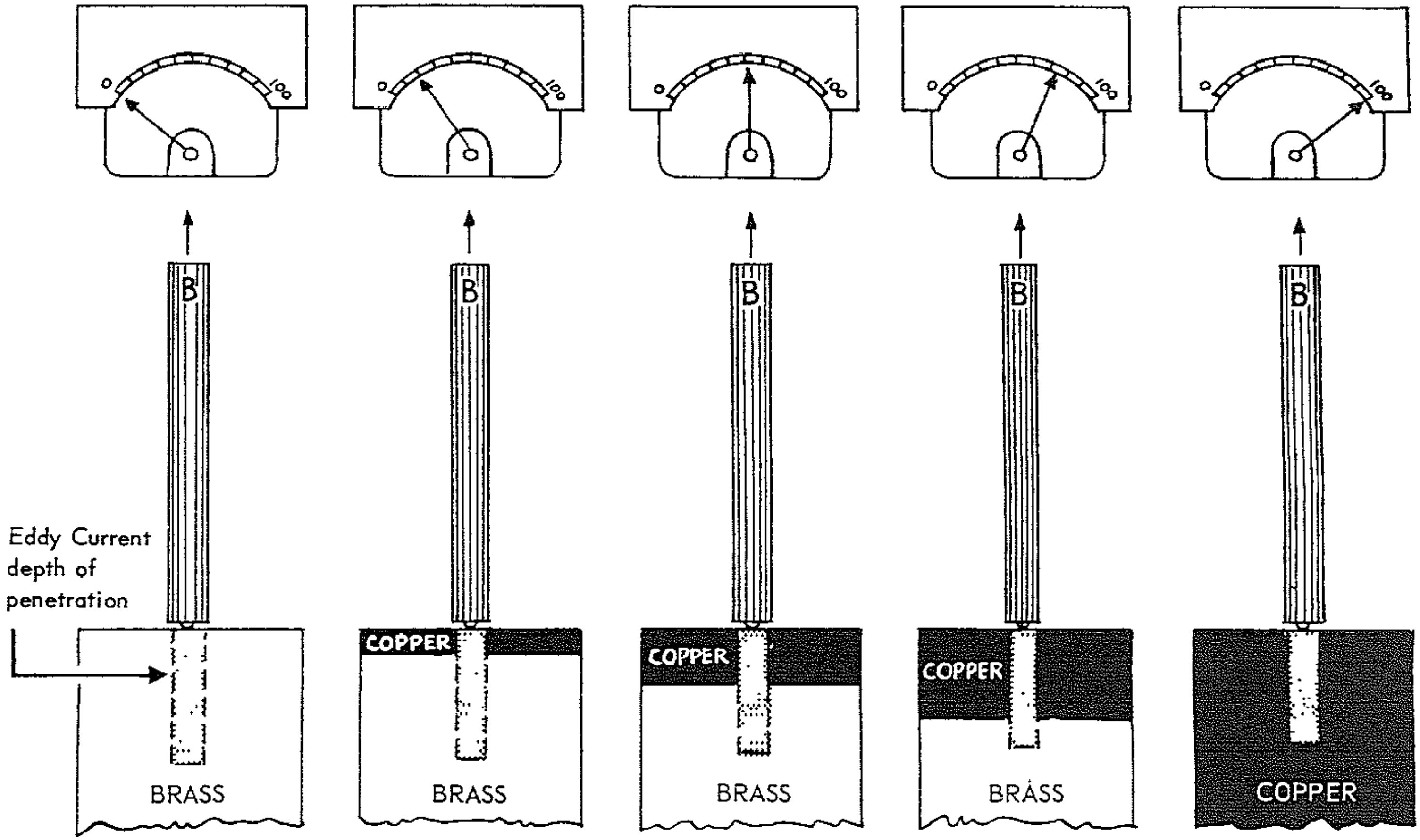


FIGURE 89. RELATIVE INSTRUMENT READINGS FOR VARIOUS THICKNESS OF COPPER PLATE ON BRASS BASE

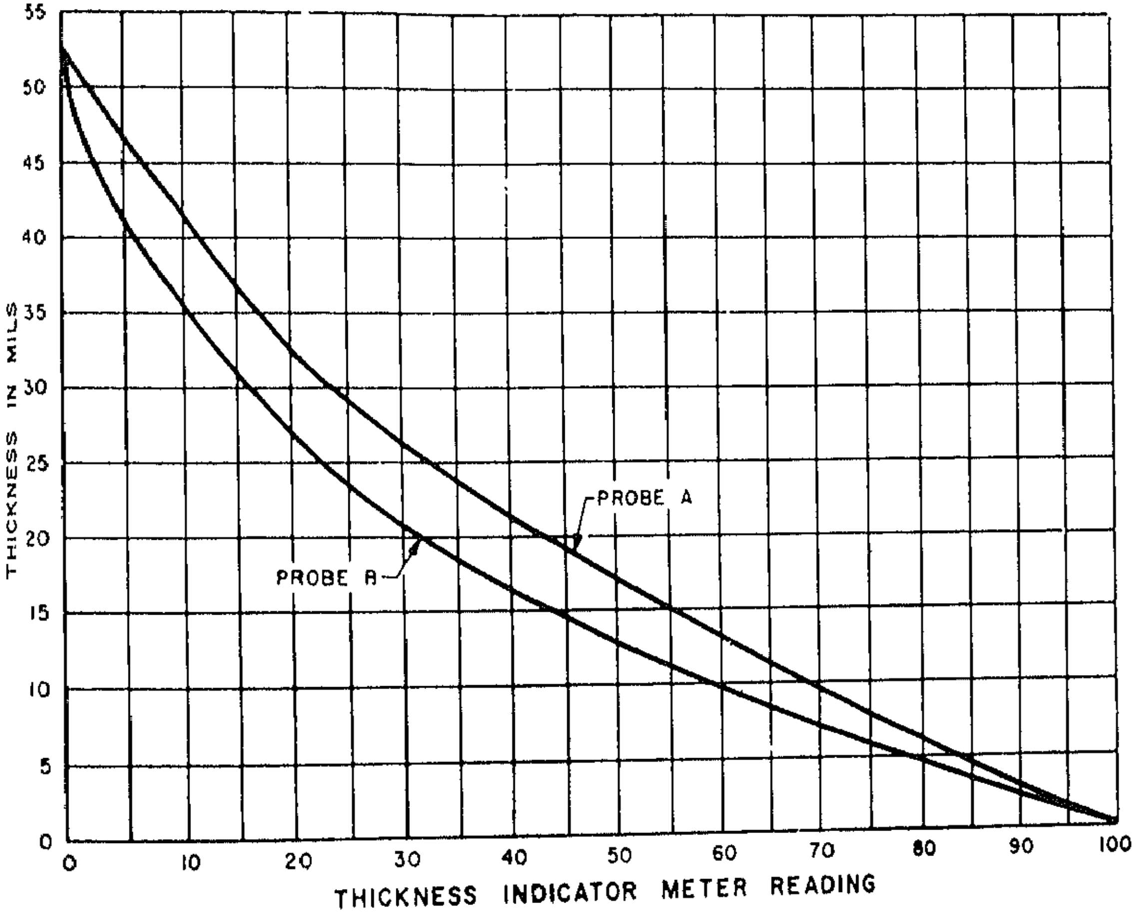


FIGURE 90. CALIBRATION CURVE OF HOT CERAMIC COATINGS ON ETP COPPER

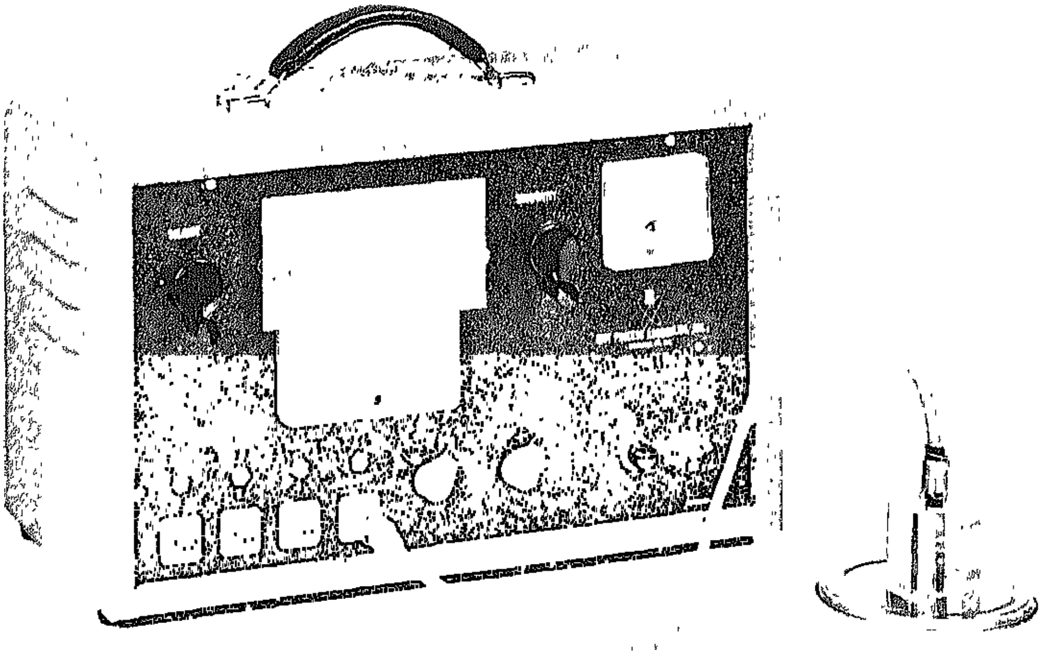


FIGURE 91. MEASURING COATING THICKNESS WITH A TEST INSTRUMENT

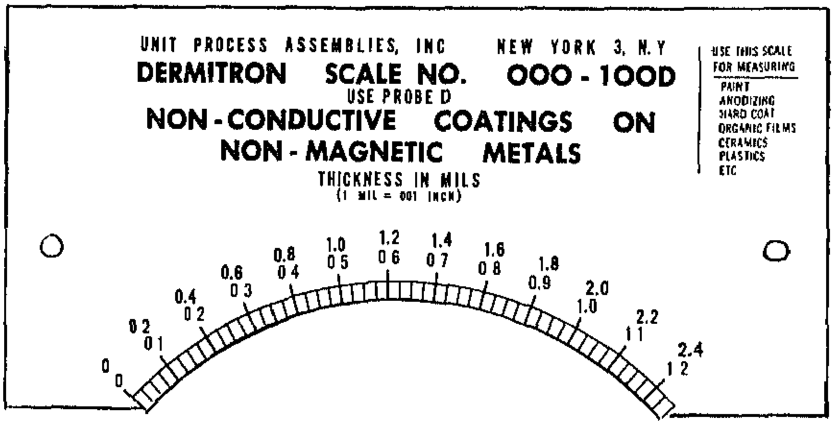


FIGURE 92. PRECALIBRATED METER SCALE

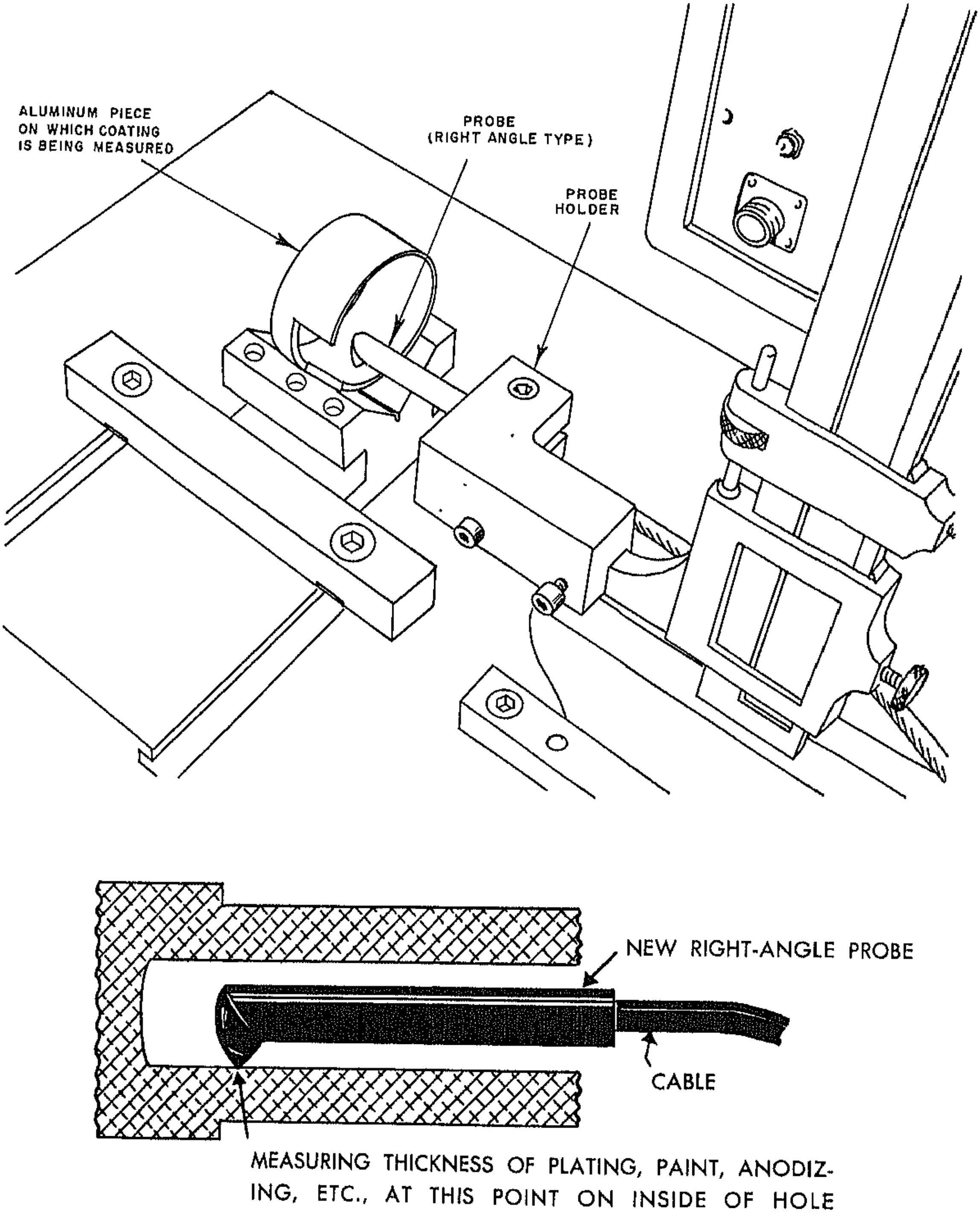
one of the commercially available electromagnetic test instruments specifically designed to measure coating thickness. The four probes cover a wide range of thicknesses of coatings. Probe A is used for measurement of thick coatings while probe D is used for thin coatings. Probes B and C are used for measurement of the intermediate range of coating thickness. Table X shows a few examples of the metal combinations and the corresponding thickness ranges covered by each probe. Figure 93 illustrates a right angle probe which is being used to measure the coating thickness on the inner diameter of an aluminum piece.

Table X. COATING THICKNESS RANGES FOR PROBES

Combination	Thickness in mils (1 mil = 0.001 inch)			
	Probe A	Probe B	Probe C	Probe D
Cadmium on steel	2.0-15.0	1.0-2.0	0.6-1.2	0-0.6
Zinc on steel	2.4-15.0	1.0-2.4	0.6-1.2	0-0.6
Copper on steel	1.0-10.0	0.4-1.0	0.2-0.4	0-0.2
Silver on steel	1.0-10.0	0.4-1.0	0.2-0.4	0-0.2
Silver on brass	2.0-5.0	1.0-2.0	0.5-1.2	0-0.7
Copper on brass	2.0-5.0	1.0-2.0	0.5-1.2	0-0.7
Copper on zinc diecast	2.0-5.0	1.0-2.0	0.7-1.2	0-0.7
Watt's nickel on steel	1.0-4.0	0.6-1.2	0.3-0.7	0.1-0.5
Non-metallic films (paint, organics, ceramics, etc. on most metals)		12-125	3-12	0.1-4.0
Anodic films on aluminum and magnesium			3-12	0.1-4.0

c. Cladding Thickness.

(1) General. In situations in which the conductivity of the two metals involved are vastly different, there are two types of cladding-thickness measurements; the first being similar to a simple thickness measurement in which the cladding is the better conductor of the two materials, and the second being similar to lift-off measurements in which the cladding is the poorer



GURE 93. RIGHT ANGLE PROBE USED TO MEASURE COATING THICKNESS ON INNER DIAMETERS

conductor of the two. Of importance is the effect of conductivity on the apparent infinite thickness of the two metals. This thickness may be easily determined experimentally for a particular metal, probe, and frequency by simply increasing the thickness of the metal specimen in steps until an increase of thickness does not change the indicated meter reading. Measurements may be made on samples of finite thickness, of course, if the thickness is held constant and an appropriate calibration is made. At a frequency of 20 kilocycles per second, a 0.030 inch thickness of copper, conductivity equal to 85 %IACS, appears infinitely thick to the eddy currents while a 0.130 inch thickness of Inconel, conductivity equal to 1.8 %IACS, is required to produce a similar effect. The apparent infinite thickness is determined not only by the frequency and conductivity of the metal, but also by the geometry of the probe coil being used. The apparent infinite thickness decreases as the diameter of the coil decreases. The accuracy of cladding thickness measurements improves as the difference between the conductivities, and hence the apparent infinite thickness, of the two metals becomes greater.

(2) Inspection of fuel plates

(a) Fuel plates used for nuclear reactors have been successfully examined for variations in nominal cladding thickness using electromagnetic techniques. These fuel plates are comprised of three layers of two different materials in sheet-form which have been compressed together to form a single plate. The core or middle layer is composed of a uranium-aluminum alloy, 48 percent uranium by weight; has a nominal thickness of 0.022 inch; and is cladded, above and below, with 6061 aluminum alloy of 0.020 inch nominal thickness to produce a heterogeneous plate having a total nominal thickness of 0.062 inch. The fuel plate is then used to form a nuclear reactor fuel element which resembles a rectangular, box-like shell having a longitudinal cross-section of 28.625 inches (length) by 2.8125 inches (width). Because of the different deformation characteristics of the core and the cladding alloy, they are frequently deformed in a nonuniform manner as the fuel plate is being rolled to achieve a specified uniform thickness. As a result, the thickness of the cladding material tends to vary inversely with the thickness of the core. Since the fuel plate is of uniform total thickness, the cladding, over the regions where the core thickness exceeds the nominal value, is much thinner than the 0.020 inch nominal thickness. Because of the possibility of from 0.003 to 0.005 inch of corrosion occurring during the life of the fuel plate, it is necessary that plates having excessive areas of undesirable cladding thickness deviations be rejected for use.

(b) A typical calibration curve relating meter deflections with thickness of cladding expressed in mils is shown in figure 94. As fuel plates are examined electromagnetically, all variations from the nominal cladding thickness are marked. For example, four of the most significant areas on one plate were sectioned as shown in figure 95, and subjected to a metallographic examination for correlation and evaluation of the eddy current measurements. Referring to figure 95, section 1 was taken through the thickest portion of the cladding on the core while section 2 was taken through the thinnest portion of the cladding (excluding the end). Sections 3 and 4 were taken through the cladding present over the "dog bone" area at the end of the core.

(c) The results of the metallographic measurements are also shown in figure 95. All measurements were made on one side of the plate only. The measurements for section 1 were made on the side of a fuel plate element containing the thickest portion of the cladding, while the remaining sections were measured on the side containing a minimum of cladding. It should be noted that in all cases where the metallographic measurement differs from the eddy current measurements, the difference is only 0.001 inch.

. GAUGING OF SHEET AND THIN PLATE THICKNESS

ne thickness of flat metal sheets and thin plates of nonferromagnetic aterial may be measured with an eddy current probe coil used in con- unction with a suitable electromagnetic test instrument, provided that many of the variables affecting the conductivity of the material can be controlled or inherently do not vary so that the predominant variable is at of thickness. This technique is most useful for thin sections. For cker sections, ultrasonic measuring techniques are much more versatile d accurate than the eddy current method. Below thicknesses of about 020 inch, however, the application of ultrasonic resonance techniques comes difficult. Fortunately, this is the range of thickness to which ly current techniques may be most effectively applied. Although the edance variations of a probe coil in proximity with a metal sheet of te thickness is somewhat similar to that of an encircling coil, mathe- ical analysis becomes largely impractical because of the large number ariables involved, and experimentally determined curves must be zed entirely.

INSPECTION OF MISCELLANEOUS END ITEMS

a. General. Electromagnetic testing techniques have been successfully lied to certain end items permitting 100 percent inspection rather than ing techniques. The discussion of the inspection of some , which follows, encompasses all the preceding areas of overs the inspection of ball bearings, jet engine parts, 14 rifle receivers.

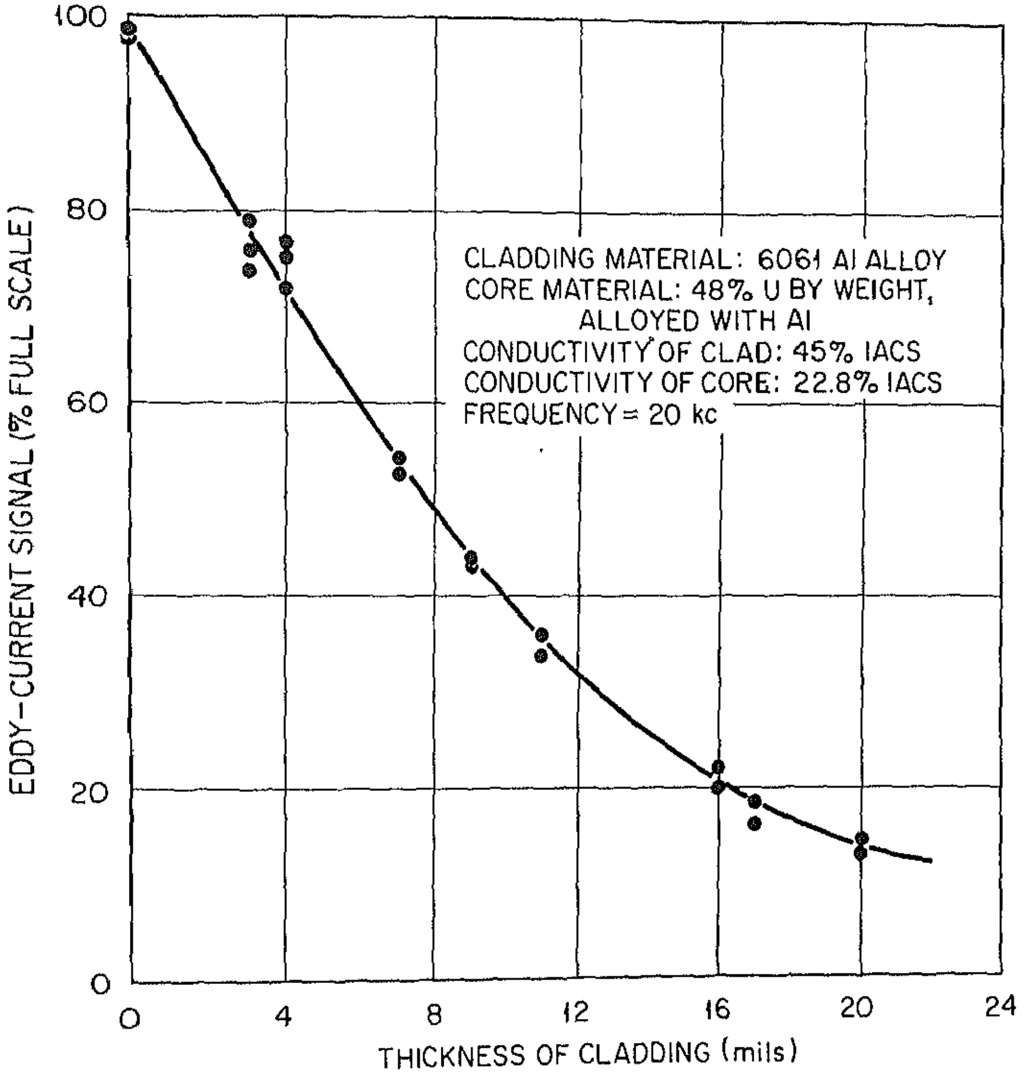
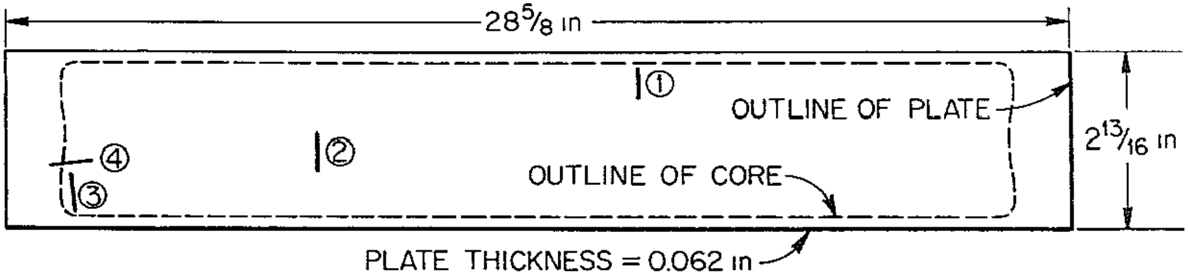
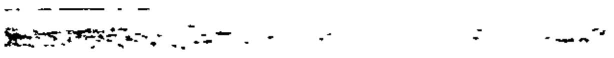


FIGURE 94. EDDY CURRENT SIGNAL CALIBRATION CURVE FOR MARK X MTR FUEL PLATES



Location of Sections Taken for Metallographic Examination (Mark X MTR Fuel Plate).

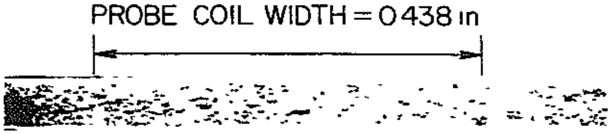
NO.1



MAXIMUM CLADDING THICKNESS BY EDDY-CURRENT INSPECTION = 0.021 in.

MAXIMUM CLADDING THICKNESS BY METALLOGRAPHIC EXAMINATION = 0.020 in

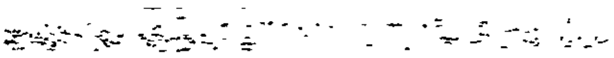
NO 3



MINIMUM CLADDING THICKNESS BY EDDY-CURRENT INSPECTION = 0.003 in.

MINIMUM CLADDING THICKNESS BY METALLOGRAPHIC EXAMINATION = 0.003 in.

NO 2



MINIMUM CLADDING THICKNESS BY EDDY-CURRENT INSPECTION = 0.010 in.

MINIMUM CLADDING THICKNESS BY METALLOGRAPHIC EXAMINATION = 0.009 in

NO 4

MINIMUM CLADDING THICKNESS BY EDDY-CURRENT INSPECTION = 0.003 in

MINIMUM CLADDING THICKNESS BY METALLOGRAPHIC EXAMINATION = 0.002 in

FIGURE 95. CROSS SECTIONS OF MARK X MTR FUEL PLATES. CLADDING-6061 ALUMINUM ALLOY. CORE-48% URANIUM BY WEIGHT AND ALLOYED WITH ALUMINUM

Ball Bearings. In making balls for ball bearings, manufacturers
e assured that they have conformed to hardness requirements.
using a standard Rockwell hardness test, only 2 to 5 percent of the
umber of balls are selected for examination. The selected samples
sumed to be representative and the test results are applied, accord-
to the entire lot. Because of the weakness of this assumption,
omagnetic testing techniques have supplanted the Rockwell hardness
various manufacturing plants. Using special test coils in conjunc-
ith a standard electromagnetic instrument, 5,000 balls may be in-
d per hour, effecting a separation of those which are either too
r too soft from those of sufficient hardness. A ball conforming to
ication hardness is placed into one of two coils. Balls to be checked
n through the second coil and are automatically compared with the
rd. Imperfect units are rejected.

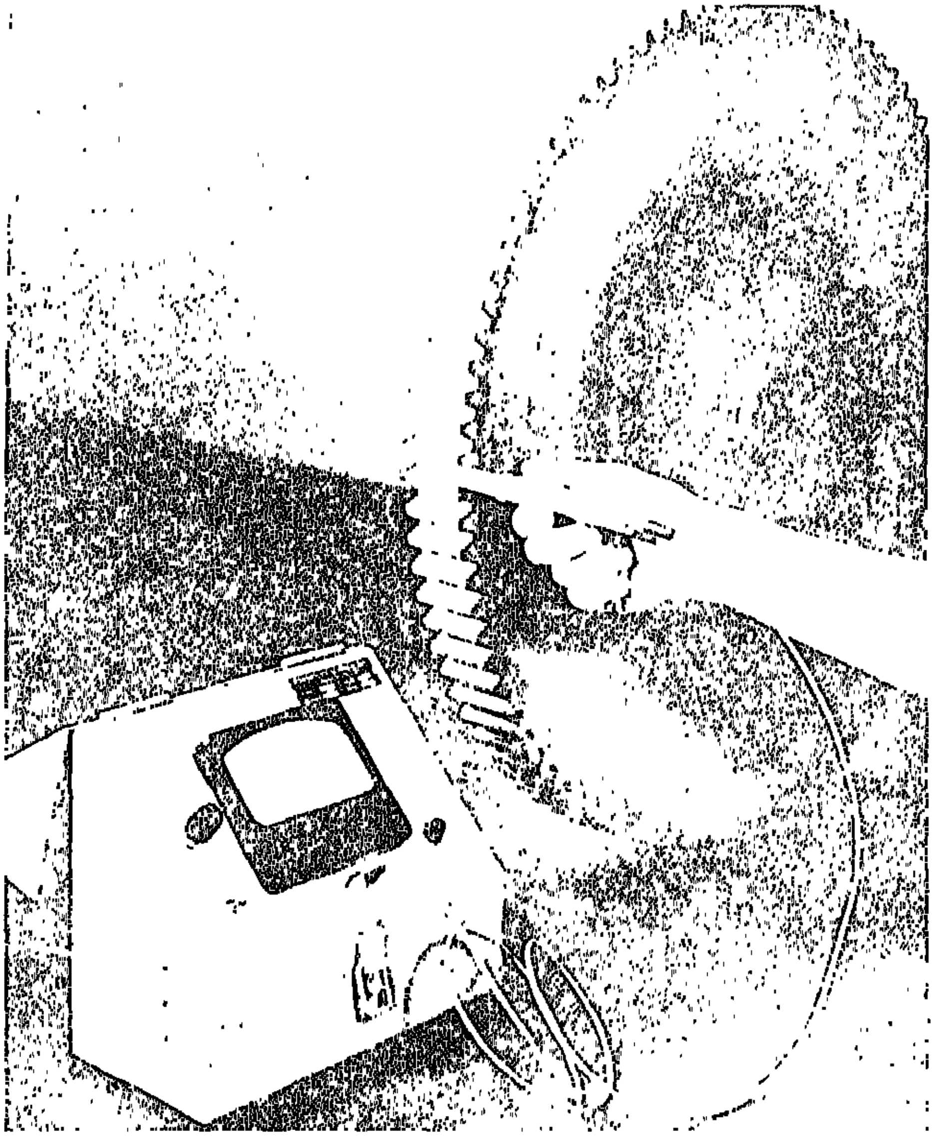
Jet Engine Parts.

(1) Periodically, turbine wheels in jet engines have broken, resulting in accidents costly in both aircraft and lives. Subsequent investigations showed that, in one type of engine, failures were of the serration type; i.e., a small chunk or chunks of material breaking loose in the blade retention area. In another engine, turbine wheels failed in a segmented manner; i.e., a large section of the wheel itself would break away. These failures have been attributed to higher than normal thermal cycling; intergranular oxidation in the bottom of broached areas and lowest serrations; and inclusions found throughout the failed areas. Such defects can initiate stress-rupture cracks which eventually progress into either a serration or segmented type failure.

(2) In these engines, then, the problem is to find the cracks before they cause failure. Until recently, fluorescent penetrant inspection methods had been employed, but were found to be limited in some respects. For example, if a crack were covered with flowed metal or filled with oxide, it could not usually be detected Because of this drawback, other nondestructive tests were tried and, after much work, an eddy current technique was selected as the most suitable for detecting cracks underlying paint, oxides, embedded inclusions, and flowed metal. Figure 96 illustrates the inspection and results of an electromagnetic test designed to locate serration cracks in an aircraft engine turbine wheel.

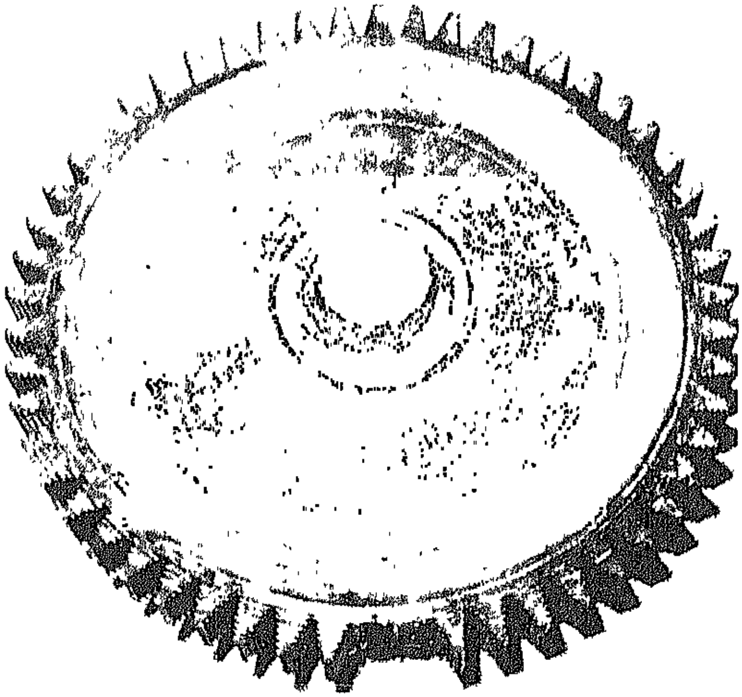
7.62-MM, M14 Rifle Receivers

(1) An investigation of several ruptured M14 rifle receivers showed that they had been made from the wrong kind of steel. Chemical analysis identified the steel as SAE 1330. The component specifications required fabrication from resulfurized SAE 8620H steel. Further screening investigations uncovered a second mixed steel which was an alloy containing 4 percent nickel.

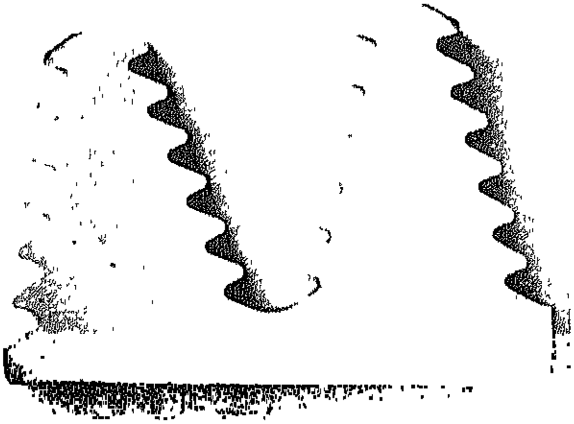


a). Electromagnetic instrument is used here to locate serration cracks in a turbine wheel. Needle fluctuates if crack is present.

FIGURE 96. ILLUSTRATION OF ELECTROMAGNETIC INSTRUMENT BEING USED TO INSPECT TURBINE WHEEL, AND SAMPLES OF FLAWS



(b). Broken turbine wheel showing breakout in blade retention area.



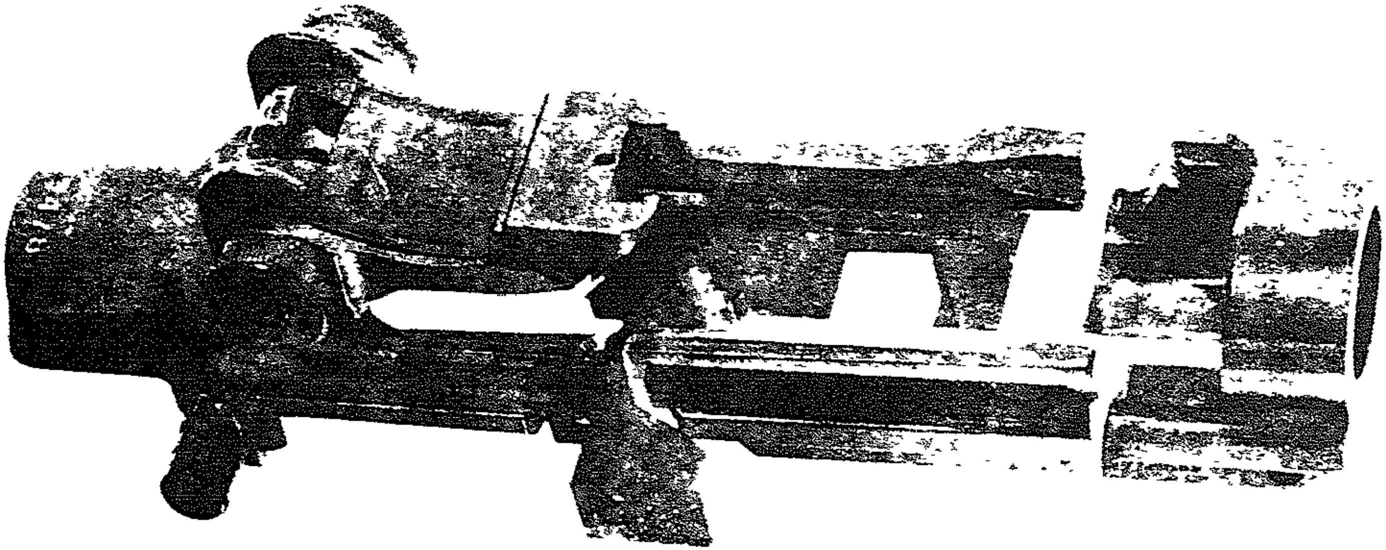
(c). The zone next to the failed area shows progression of fatique crack across bottom of "Christmas tree".

FIGURE 96 (Cont). ILLUSTRATION OF ELECTROMAGNETIC INSTRUMENT BEING USED TO INSPECT TURBINE WHEEL, AND SAMPLES OF FLAWS

l). Oxide-filled cracks (above) and intergranular cracks (below) can be detected by electromagnetic tests. (Above) Etchant: none; 500x. (Below) Etchant: 92% HCL, 5% H_2SO_4, 3% HNO_3 (modified Tucker's etch); 200x.

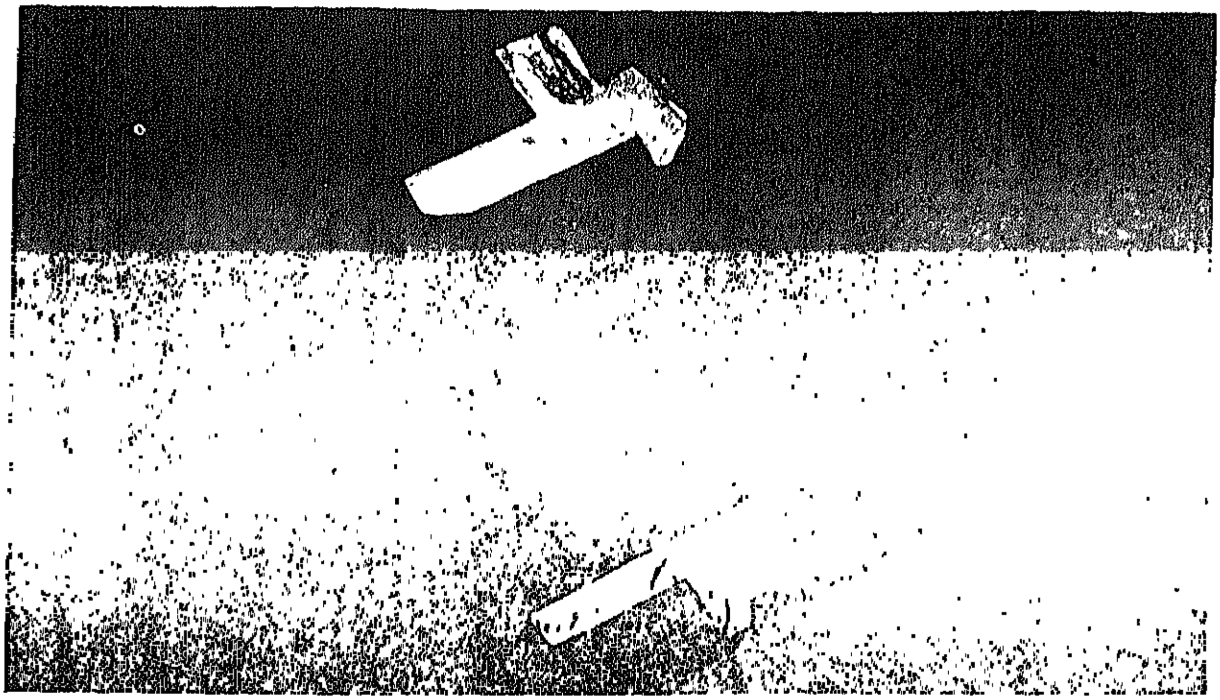
FIGURE 96 (Cont). ILLUSTRATION OF ELECTROMAGNETIC INSTRUMENT BEING USED TO INSPECT TURBINE WHEEL, AND SAMPLES OF FLAWS

(2) Electromagnetic testing techniques were successful in separating the M14 rifle receivers according to the three different steels used. The method consisted of using differential coil configurations in conjunction with two test instruments capable of indicating the amplitude, phase, and waveform harmonic content of the test signal. The underlying principle of the test was the comparison of the effective permeabilities of the untested receivers, with respect to a standard reference receiver conforming to specifications which remained in one of the test coils throughout the test. Lower permeability values were indicated by positive meter deflections, and higher permeability values by negative meter deflections. Thus, it was possible to screen out all receivers not conforming to the standard. Phase shifts and wave harmonic content of the test signal were also observed on cathode-ray-tube displays. Photographs of the test equipment, meter readings, and scope patterns are shown in figures 97 to 99.



(a). Damaged M14 rifle receiver after firing one test round.

FIGURE 97. DAMAGED M14 RIFLE RECEIVER



(b). Close-up view of the damaged M14 rifle receiver

FIGURE 97 (Cont). DAMAGED M14 RIFLE RECEIVER

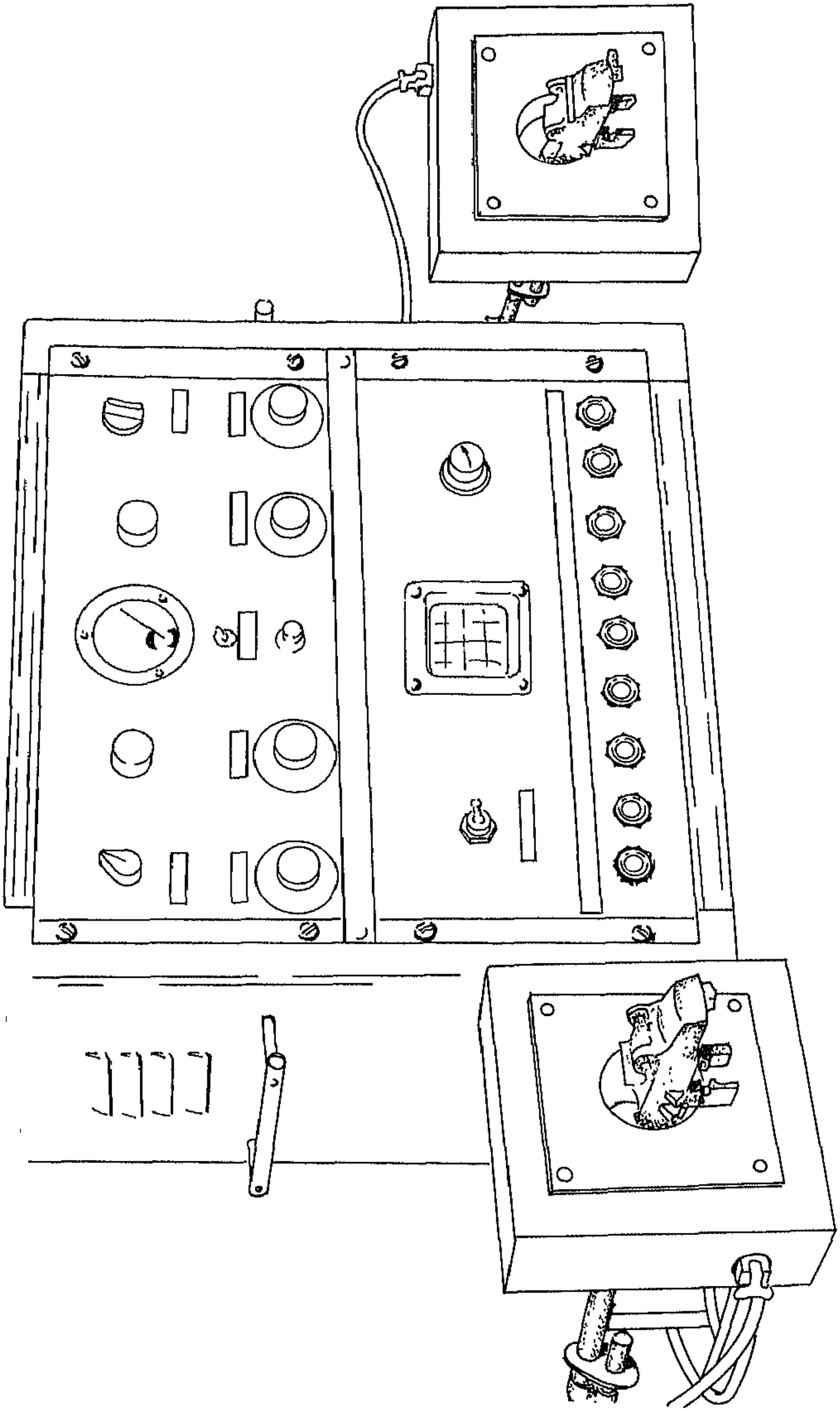
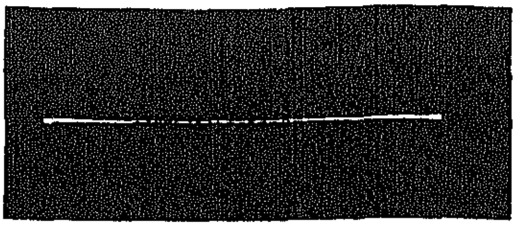


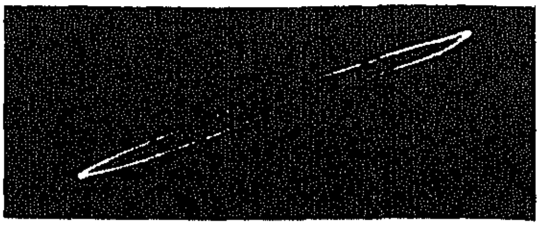
FIGURE 98. ELECTROMAGNETIC TEST EQUIPMENT USED FOR THE INSPECTION OF M14 RIFLE RECEIVERS

8620 H Material Receiver



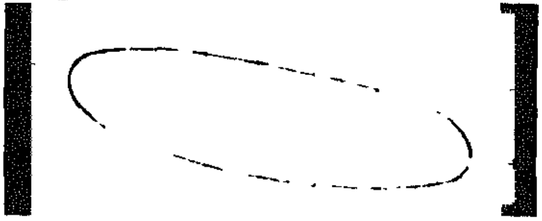
Meter Reading 0

1330 Material Receiver

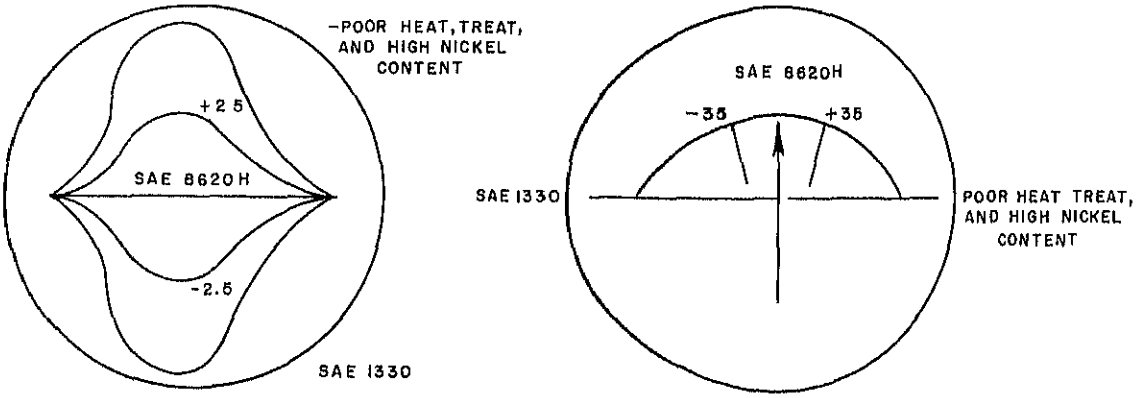


Meter Reading +100

High Nickel Material Receiver



Meter Reading -100



Alloy sorting indication on Magnatest FS-300 unit

Alloy sorting indication on Magnetic Analysis Comparator

FIGURE 99. ALLOY SORTING INDICATIONS: METER READINGS AND SCOPE PATTERNS

APPENDIX

SYMBOLIC DEFINITIONS USED IN ELECTROMAGNETIC TESTING THEORY

Symbol	Quantity	Units mks*	 cgs**
B	Induced magnetic field, flux density	weber/m^2	gauss
B_m	Maximum intrinsic flux density	weber/m^2	gauss
B_r	Remanence (or retentivity)	weber/m^2	gauss
cgs	Centimeter-gram-second	-	
δ	Depth of penetration	-	
e	Electron	coulomb	
E or V	Voltage	volts	
f	Frequency	cycles/sec	
f_c	Characteristic frequency	cycles/sec	
H	Applied magnetic field, magnetic force, field strength	amp-turn/m	oersted
H_c	Coercive force	amp-turn/m	oersted
I	Current	ampere	
Φ or J	Line of flux	weber	maxwell
L	Inductance	henry	
μ	Permeability	henry/m	gauss/oersted
μ_m	Maximum permeability	henry/m	gauss/oersted
μ_o	Permeability of free space (or vacuum)	henry/m	gauss/oersted
μ_R	Relative magnetic permeability	henry/m	gauss/oersted
M	Magnetization (defined as $M = B - \mu_o H$)	-	
mks	Meter-kilogram-second	-	
N	Fill factor	-	
ρ	Resistivity	ohm-m	ohm-cm
R	Resistance	ohm	
$\mathcal{R}$	Reluctance	amp-turn/ weber	gilbert/max

Symbol	Quantity	Units	
		mks*	cgs**
σ	Conductivity	mho/m	mho/cm
Z	Impedance	ohm	
ω	Angular frequency	radian/sec	
ωL	Inductive reactance	ohm	

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*rationalized mks units

**practical cgs units

- abbreviations in Units column: m = meter; cm = centimeter; max = maxwell

GLOSSARY OF TERMS USED IN ELECTROMAGNETIC TESTING

ABSOLUTE - Refers to measurements made without a direct reference in contrast to differential measurements.

ABSOLUTE SIGNAL - The value of the amplitude of a signal without consideration of its relative phase, frequency or waveform.

ANALYSIS, IMPEDANCE - Refers to an analytical method which consists of correlating changes in the amplitude, phase, and/or quadrature components of a complex test signal voltage to the electromagnetic conditions within the test specimen.

ANALYSIS, MODULATION - An instrumentation method used in electromagnetic testing which separates responses due to various factors influencing the total magnetic field by separating and interpreting individually, frequencies or frequency bands in the modulation envelope of the (carrier frequency) signal.

ANALYSIS, PHASE - An instrumentation technique which discriminates between variables in the test part by the different phase angle changes which these conditions produce in the test signal.

COIL - One or more turns of conductor wound to produce a magnetic field when current passes through the conductor.

COIL, ABSOLUTE - A coil (or coils) that respond(s) to all electromagnetic properties of the test part.

COIL, BOBBIN - A coil or coil assembly used for electromagnetic testing by insertion into the test piece as in the case of an inside probe for tubing. Coils of this type are also referred to as inside coils or inserted coils.

COIL, ENCIRCLING - Refers to coil(s) or coil assembly which surround(s) the part to be tested. Coils of this type are also referred to as annular, circumferential, or feed-through coils.

COIL, PROBE - Refers to a small coil or coil assembly which does not encircle the test specimen.

COIL, SEARCH - Refers to a probe coil which is used to measure local magnetic field intensities by virtue of the change of flux through the coil when it is moved from one position to another, or when the flux through it is changed by any other means.

COILS, BUCKING - See COILS DIFFERENTIAL.

COILS, DIFFERENTIAL - Two or more coils electrically connected in series opposition such that any electromagnetic condition which is not common to the areas of the specimen being tested or the test specimen and the standard will produce an unbalance in the system and, thereby, be detected.

COIL CLEARANCE, ANNULAR (Also called COIL SPACING) - Refers to an encircling coil assembly surrounding a cylindrical test piece and equals the mean radial distance between the adjacent coil assembly and test part surface.

COIL CLEARANCE, PROBE - Perpendicular distance between adjacent surfaces of the coil(s) and test part. (See EFFECTIVE LIFT-OFF).

COIL SIZE - Refers to geometry or dimension of a coil, e.g., length, diameter.

COIL SPACING - (a) Refers to the axial distance between two encircling coils of a differential system, or (b) as per definition in COIL CLEARANCE ANNULAR.

COUPLING - An interaction between systems, or between properties of a system.

DEPTH OF PENETRATION - Refers to that depth at which the magnetic field strength or intensity of induced eddy currents has decreased to 37 percent of its surface value. The depth of penetration is an exponential function of the frequency of the signal, and the conductivity and permeability of the material. Synonymous terms are Standard Depth of Penetration and Skin Depth. (See SKIN EFFECT.)

DEPTH OF PENETRATION, EFFECTIVE - Refers to that minimum depth beyond which a test system can no longer detect a further increase in specimen thickness.

DETECTION, PHASE - The derivation of a signal whose amplitude is a function of the deviation in phase of a single frequency alternating quantity, such as voltage or current, from a similar quantity of a fixed phase.

IAGRAM, IMPEDANCE PLANE - Refers to a graphical representation of the locus of points indicating the variations in the impedance of a test coil as a function of basic test parameters.

FFERENTIATED - Refers to an output signal which is proportional to the rate of change of the input signal.

ISCONTINUITY, ARTIFICIAL - Refers to reference discontinuties, such as holes, grooves, or notches, which are introduced into a reference standard to provide accurately reproducible sensitivity levels for electromagentic test equipment.

DISTORTION, HARMONIC - Nonlinear distortion characterized by the appearance in the output of harmonics other than the fundamental component when the input wave is sinusoidal. Harmonic distortion is sometimes called amplitude distortion.

EDDY CURRENTS - Currents caused to flow in an electrical conductor by the time and/or space variation of an applied magnetic field.

EDDY CURRENT TESTING - A nondestructive testing method in which eddy current flow is induced in the test object. Changes in the flow caused by variations in the specimen are reflected into a nearby coil or coils for subsequent analysis by suitable instrumentation and techniques.

EFFECT, END - The effect on the magnetic field caused by the geometric boundaries of the test specimen that makes it impractical to apply electromagnetic test methods to the associated regions of the test specimen. This effect is also referred to as the Edge Effect.

EFFECT, LIFT-OFF - Refers to the effect observed in the test system output due to a change in magnetic coupling between a test specimen and a probe coil whenever the distance of separation between them is varied.

EFFECT, SKIN - Refers to the phenomena wherein the depth of penetration of electric currents into a conductor decreases as the frequency of the current is increased. At very high frequencies, the current flow is restricted to an extremely thin outer layer of the conductor. (See DEPTH OF PENETRATION.)

EFFECT, SPEED - Refers to the phenomenon in electromagnetic testing which evidences itself as a change in the signal voltage resulting from emf's produced by the relative motion between a specimen and a test coil assembly. These emf's cause eddy currents which result in a space redistribution of the magnetic field.

ELECTROMAGNETIC TESTING - Refers to that nondestructive test method for engineering materials, including magnetic materials, which use electromagnetic energy having frequencies less than those of visible light to yield information regarding the quality of the material tested.

FILL FACTOR - The ratio of the square of the diameter of a cylindrical test specimen to the square of the average diameter of the encircling coil.

FLUX, LEAKAGE - Magnetic lines of force which leave and enter the surface of a part due to a discontinutiy which forms poles at the surface of the part.

FREQUENCY, OPTIMUM - That frequency which provides the highest signal-noise ratio obtainable for the detection of an individual property such as conductivity, crack, inclusion, etc., of the test specimen. Each type of defect in a given material may have its own optimum frequency.

FREQUENCY, TEST - Refers to the number of complete input cycles per unit time of a periodic quantity such as alternating current. The test frequency is always considered to be the fundamental whenever harmonics are generated in the process of testing certain materials such as ferromagnetic materials.

IACS - International Annealed Copper Standard is an international standard of electrical conductivity.

IMPEDANCE PLANE DIAGRAM - Refers to a graphical representation of the locus of points indicating the variations in the impedance of a test coil as a function of basic test parameters.

LEVEL, TEST QUALITY - Refers to the sensitivity at which a test is performed.

LEVEL, REJECTION - The setting of the signal level above or below which all parts are rejectable or in an automatic system at which objectionable parts will actuate the reject mechanism of the system.

MATERIAL, DIAMAGNETIC - A material having a permeability less than that of a vacuum.

ATERIAL, FERROMAGNETIC - A material which, in general, exhibits hysteresis phenomena, and whose permeability is dependent on the magnetizing force.

MATERIAL, NONFERROMAGNETIC - A material that is not magnetizable and hence, essentially not affected by magnetic fields. This would include paramagnetic materials having a magnetic permeability slightly greater than that of a vacuum, and approximately independent of the magnetizing force and diamagnetic materials having a permeability less than that of a vacuum.

ATERIAL, PARAMAGNETIC - A material having a permeability which is slightly greater than that of a vacuum, and which is approximately independent of the magnetizing force.

OISE - Refers to any undesired signal that tends to interfere with the normal reception or processing of a desired signal. In flaw detection, undesired response to dimensional and physical variables (other than flaws) in the test part is called "part noise".

ERMEABILITY, EFFECTIVE - A hypothetical quantity which is used to describe the magnetic field distribution within a cylindrical conductor in an encircling coil. The field strength of the applied magnetic field is assumed to be uniform over the entire cross-section of the test specimen with the effective permeability, which is characterized by the conductivity and diameter of the test specimen and test frequency, assuming values between zero and one, such that its associated amplitude is always less than one within the specimen.

PERMEABILITY, INCREMENTAL - The ratio of the cyclic change in magnetic induction to the corresponding cyclic change in magnetizing force when the mean induction differs from zero.

PERMEABILITY, INITIAL - Refers to the slope of the normal induction curve at zero magnetizing force.

PERMEABILITY, NORMAL - The ratio of the normal induction to the corresponding magnetizing force.

PERMEABILITY VARIATIONS OF A MATERIAL - Refers to magnetic inhomogeneities of a material.

PHASE ANGLE - Phase angle is the angular equivalent of the time displacement between corresponding points on two sine waves of the same frequency.

PHASE SHIFT - A change in the phase relationship between two alternating quantities of the same frequency.

READOUT, ABSOLUTE - Refers to the signal output of an absolute coil.

READOUT, DIFFERENTIAL - Refers to a signal output obtained from a differential coil system.

RELUCTANCE, CIRCUIT - The reluctance of the magnetic circuit is the algebraic sum of the reluctances of each portion of the circuit.

RESOLUTION, DEFECT - A property of a test system which enables the separation of signals due to defects in the test specimen that are located in close proximity to each other.

RESPONSE, AMPLITUDE - Refers to that property of the test system whereby the amplitude of the detected signal is measured without regard to phase.

SATURATION - Refers to the degree of magnetization produced in a ferromagnetic material for which the incremental permeability has decreased substantially to unity.

SELECTIVITY - Refers to the characteristic of a test system which is a measure of the extent to which an instrument is capable of differentiating between the desired signal and disturbances of other frequencies or phases.

SENSING HEAD - Refers to a probe unit containing a coil, magnet, or magnetic circuit from which a test signal is derived.

SIGNAL GRADIENT - See READOUT, DIFFERENTIAL.

SIGNAL-NOISE-RATIO - Refers to that ratio of values of signal (response containing information) to that of noise (response containing no information).

STANDARD - (1) A reference used as a basis for comparison or calibration. (2) A concept that has been established by authority, custom, or agreement to serve as a model or rule in the measurement of quantity or the establishment of a practice or a procedure.

STANDARD, REFERENCE - A reference used as a basis for comparison or calibration.

SYSTEM, PHASE SENSITIVE - A system whose output signal is dependent on the phase relationship between an input and a reference voltage.

TIME, RECOVERY - Refers to the time required for a test system to return to its original state after it has received a signal.

WOBULATION - Refers to an effect which produces variations in an output signal of a test system and arises from variations in coil spacing due to lateral motion of the test specimen in passing through an encircling coil.

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