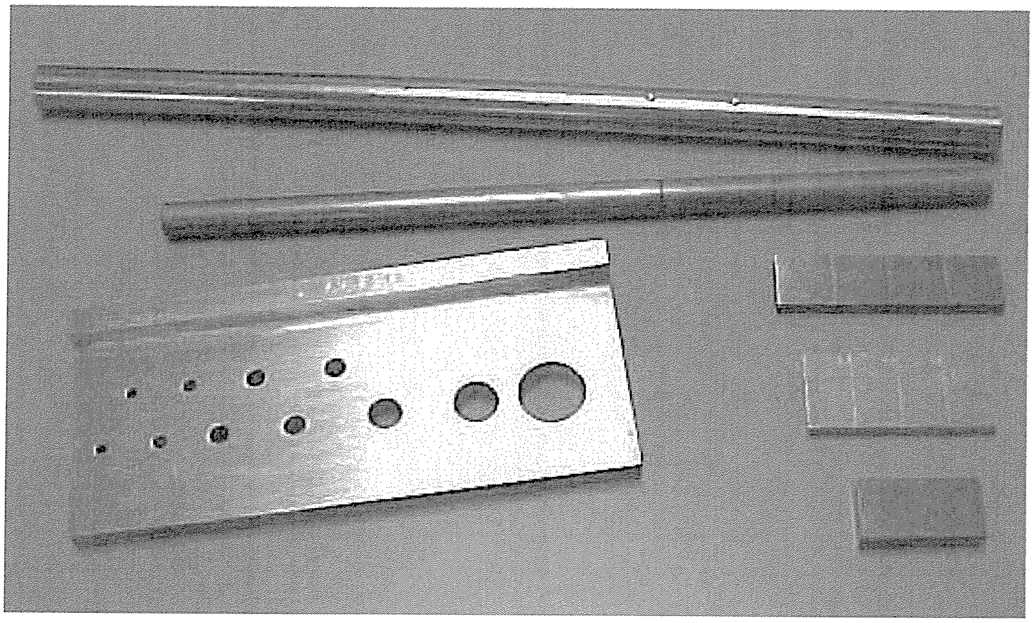


FIGURE 8-42 Reference standards.

service or rejected during manufacture. These are invaluable in sharpening one's interpretive skills.

8.6 EDDY CURRENT APPLICATIONS AND SIGNAL DISPLAY

8.6.1 Eddy Current Display Media

Eddy current testing employs a variety of display media, including:

- Graphic displays, such as cathode ray tubes, liquid crystal screens, and electroluminescent screens
- Analog and digital meter displays
- Simple "go/no-go" displays such as light emitting diode illumination to indicate a deviation of impedance from a reference signal (e.g., detection of a surface crack)
- Recording devices, such as strip charts, magnetic tape, and floppy disks that enable postinspection analysis of test data

Graphic display screens are the prevalent media for obtaining detailed, real-time test information. These displays include:

- A sinusoid showing amplitude and phase variations of total voltage across the coil
- An ellipse that tilts and varies in shape as the test material varies in geometric properties and conductivity
- Deflections of a timebase sweep

- Impedance plane display
- X–Y output of impedance plane display

The sinusoid and ellipse presentations are essentially obsolete, having been replaced by impedance plane displays; but test systems using these outputs may still be in use. The time base is used to show discontinuity location over a defined range of test coil movement, such as the 360° sweep of a coil rotating in a bolt hole; however, time base display is limited in that it indicates signal amplitude but not phase information. Impedance plane display shows complete eddy current signal information and is generally the most useful for signal analysis. The X–Y output of the impedance plane can be sent to various recording and storage media, and is also available on the display screen of some instruments.

8.6.2 Impedance Plane Display

The impedance plane is the key to signal interpretation as well as to obtaining optimum test results. As stated earlier, the impedance plane is a graph of test coil impedance variations with inductive reactance displayed on the vertical axis and resistance on the horizontal. The point on the graph representing the test coil when it is remote from any conductive material is an important display reference position. It is called the "coil in air" or simply "air" point for surface and internal coils and the "empty coil" point for encircling coils (Figure 8-43a). For the remainder of this discussion, the term "air point" will be used, regardless of coil configuration.

As the test coil is brought into proximity with a test specimen, the display dot makes a trajectory from the air point to a point representing the impedance of the test specimen (Figure 8-43b). Each condition that eddy current testing can detect is characterized by a unique position or pattern on the impedance plane, with test variables generally arranged along curves, such as the conductivity curve shown in Figure 8-43c, that are obtained by joining the end-points of the series of lift-off curves. The curves may properly be termed "loci" in that they trace a set of points that represent the range of some variable to which eddy current testing is sensitive.

The impedance plane can be manipulated to advantage by altering parameters such as test frequency and coil diameter. The best presentation is usually a compromise, in that sensitivity, penetration, and resolution are all affected by changes in frequency and coil specifications. By studying impedance graphs and their manipulation, the practitioner can anticipate and optimize test signals for a given application.

Normalization of the Impedance Plane

The sensitivity of the impedance plane to alteration of test parameters does present one problem: changes in these parameters, since they change coil impedance, also change the position and scale of the curves that indicate test material variations. Thus, every change in frequency and/or coil specifications results in a new set of impedance curves. The problem can be illustrated by the effect of frequency variation on inspection of very thin-walled tube with an encircling coil. Figure 8-44a shows that, without the tube inserted, changes in frequency cause changes in inductive reactance values for the coil. That is, five different frequencies result in five different positions for the air point. Figure 8-44b shows curves for variation in conductance from each air point to infinity, with the dashed lines showing the effect of inserting tubes of different conductance into the coil. As frequency is increased, a given tube's impedance takes a more clockwise position on a larger curve. However, the proliferation of curves can be solved with normalization. The impedance plane is normalized by converting the vertical axis from a scale of inductive

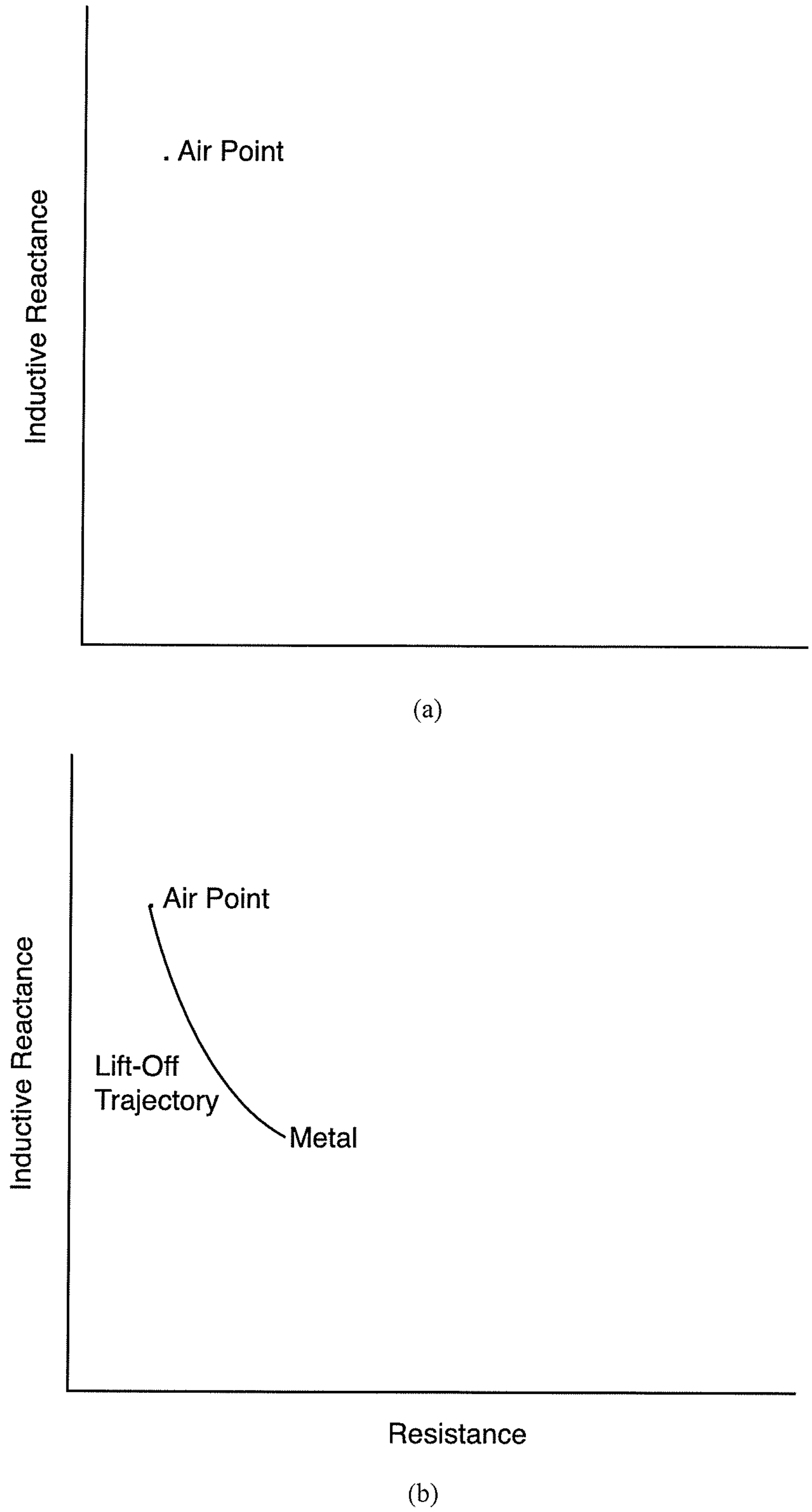
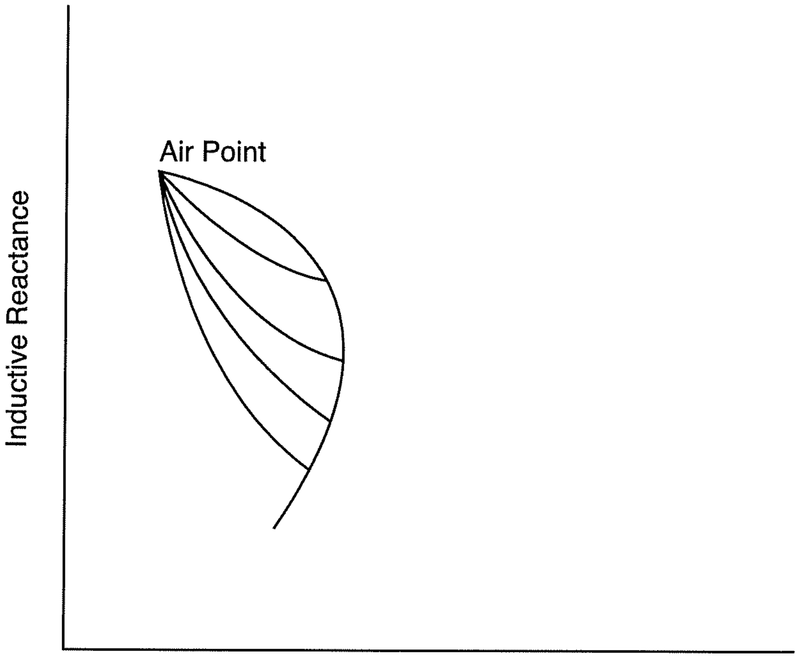


FIGURE 8-43 Impedance plane: (a) air point, (b) lift-off trajectory.



(c)

FIGURE 8-43 (c) Conductivity curve.

reactance of the test coil in ohms to a scale of inductive reactance of the test coil compared to the inductive reactance of the coil's own air point; this is done by dividing actual coil inductive reactance by inductive reactance at the air point. This has the effect of mathematically pulling all of the curves shown in Figure 8-44b into a single curve. Additionally, the horizontal axis needs to be normalized; this is done by subtracting variations in coil wire resistance from total resistance (one is interested in displaying test specimen variations, not coil variations) and dividing the remainder by the inductive reactance at the air point. Thus, the normalized impedance plane would be labeled $\omega L/\omega L_0$ on the vertical axis and $R/\omega L_0$ on the horizontal.

Most of the remaining illustrations will show a normalized impedance plane. However, in some cases it will be more convenient to illustrate the subject matter using a nonnormalized impedance plane, with the assumption that frequency and coil properties are fixed.

Effect of Phase Lag on the Conductance Curve

Figure 8-44b showed that impedance traces a semicircular path when conductance in a very thin-walled tube is varied . The semicircular pattern results when the specimen wall is so thin that phase lag is insignificant. Factors that increase current flow result in clockwise movement of the impedance operating point along the semicircle, while those that restrict current flow result in counterclockwise movement of the operating point, as seen in Figure 8-45.

As specimen wall thickness is increased, display of test variables becomes more complicated, with the semicircle evolving into a comma shape and dimensional variations ap-

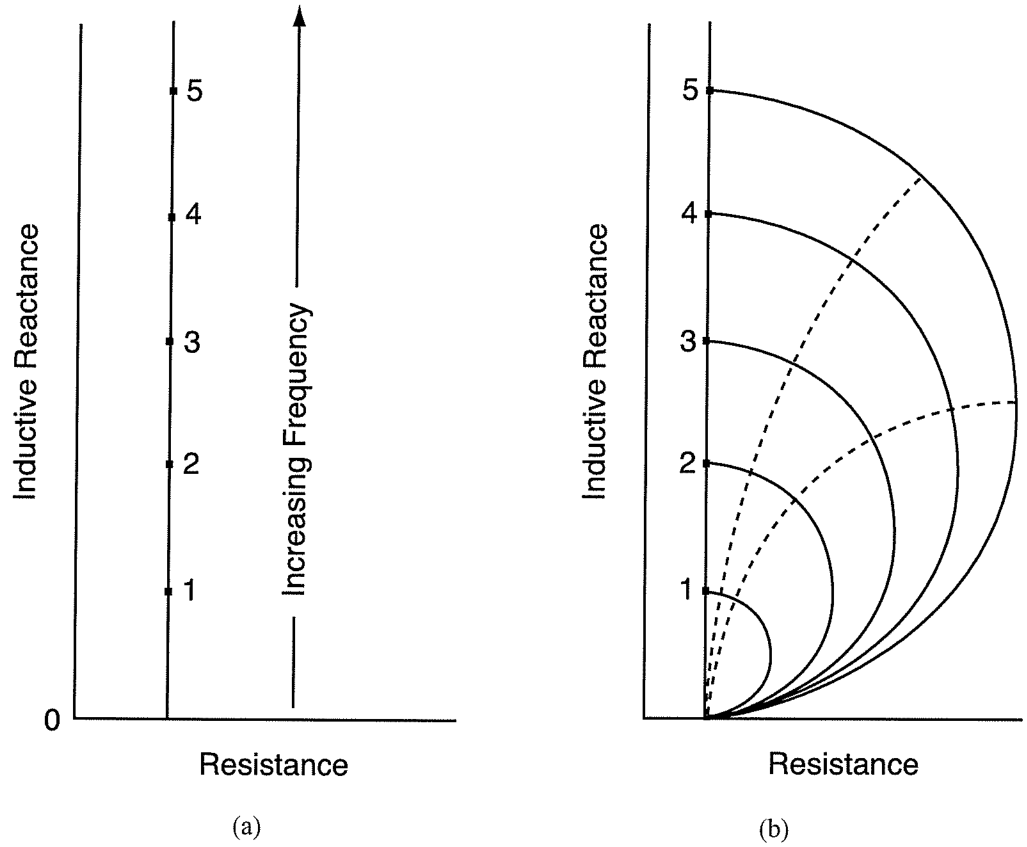


FIGURE 8-44 Impedance plane before normalization. (a) Movement of air point with change in frequency. (b) Variation of conductance with frequency.

pearing as appendages to the comma curve. The shaded area in Figure 8-46a shows how the semicircular impedance curve changes from a semicircle to a comma shape as a very thin-walled tube inside an encircling coil transforms into a solid bar. The semicircular curve is also valid for very thin-walled tubes inspected by an internal coil. In the case of a solid bar inside a long encircling coil, a "perfect comma" is achieved, with the lower end of the curve intersecting the origin of the graph at a 45° angle. The comma-shaped curve that evolves due to increased wall thickness is normally called a conductivity curve, although variations in frequency and coil diameter also cause movement along this curve on the normalized impedance plane. Internal coils testing thicker tubes, as well as surface coil applications, produce a more flattened impedance curve, similar to that shown in Figure 46b.

Lift-Off Curves

When a test coil is remote from any conductive material, impedance is at a position of high inductive reactance and low resistance. The high value for the air point on the inductive reactance scale occurs because there is no secondary flux available to reduce primary flux; the low value on the resistance scale occurs because the only resistance detected is that of the coil wire.

As the coil approaches a conductive and/or ferromagnetic object, the impedance of

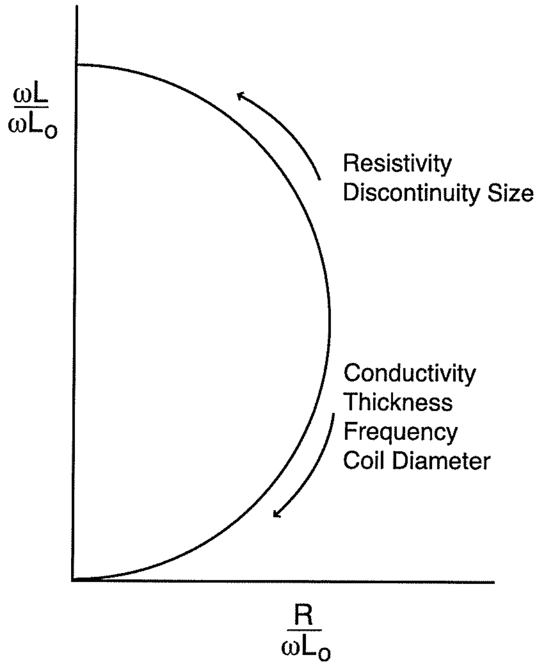
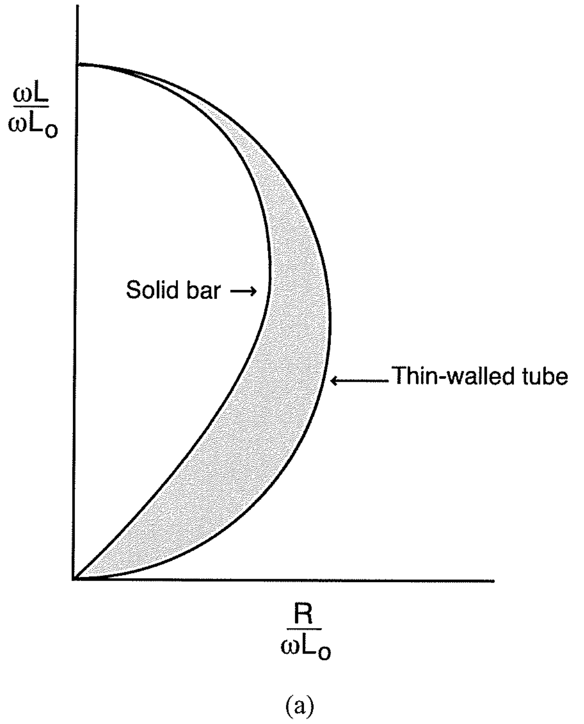


FIGURE 8-45 Effect of test variables on impedance curve operating point.

the coil changes and the display dot moves. If the coil approaches a nonferromagnetic conductive specimen, secondary flux cancels a portion of primary flux, resulting in a decrease in inductive reactance, as shown in Figure 8-47a. The more conductive the test material, the greater the cancellation of primary flux and the further downward the display dot moves. Simultaneously, the specimen acts as a resistive load on the coil and the impedance point advances along the resistance scale. However, if the coil approaches a specimen that is both ferromagnetic and conductive, the specimen's flux adds to the coil's flux and the impedance point moves up both the inductive reactance and resistance scales, as shown in Figure 8-47b. If the material is nonconductive (such as ferrite), the impedance point advances up the inductive reactance axis only, Figure 8-47c, with no movement along the resistance axis. This effect is useful in orienting phase rotation to achieve a vertical deflection for inductive reactance variation. Regardless of direction, the display dot trajectory is the vector sum of movement along both axes and is called a lift-off curve.

Just as the spacing between a surface coil and the test material is called "lift-off"; the spacing between either an internal coil or encircling coil and concentrically positioned test material is called "fill factor". As stated earlier, lift-off is useful for measuring the thickness of nonconductive coatings on metals. Moreover, it can be used to measure the thickness of any nonconductive material that is simply resting on a conductive surface. Fill factor can be used to measure diameter of bars and rods placed inside encircling coils. Sensitivity to lift-off and fill factor depends on flux density and thus decreases as coil to test material distance increases. The decrease in sensitivity is, of course, nonlinear because flux density decreases according to the inverse square law.

The downside of sensitivity to lift-off and fill factor variations is that inadvertent movement of the coil relative to the test material will cause noise signals that can obscure the signals for which the test is being performed. Prevention of noise signals due to lift-



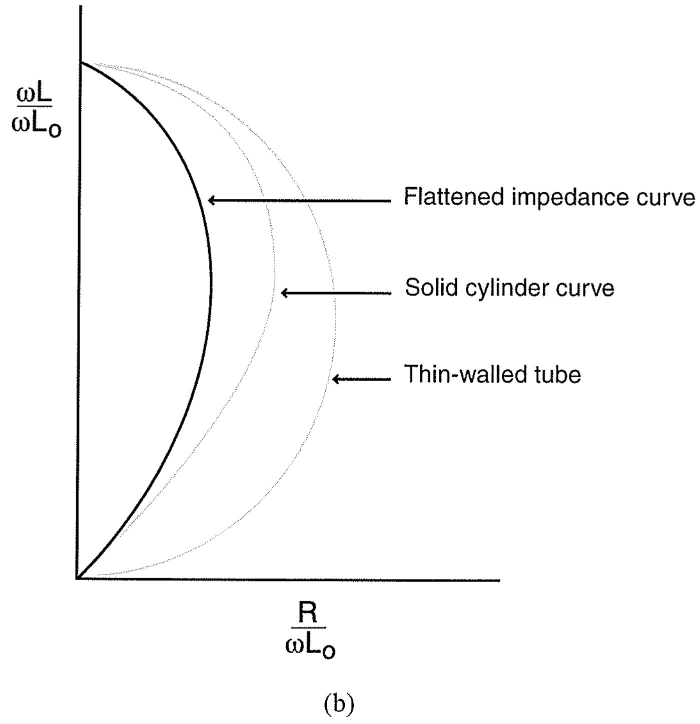


FIGURE 8-46 Variation of impedance curve shape with specimen configuration. (a) Transition of impedance curve from semicircle to comma shape. (b) Impedance curves for internal coil testing thicker tubes and for surface coils.

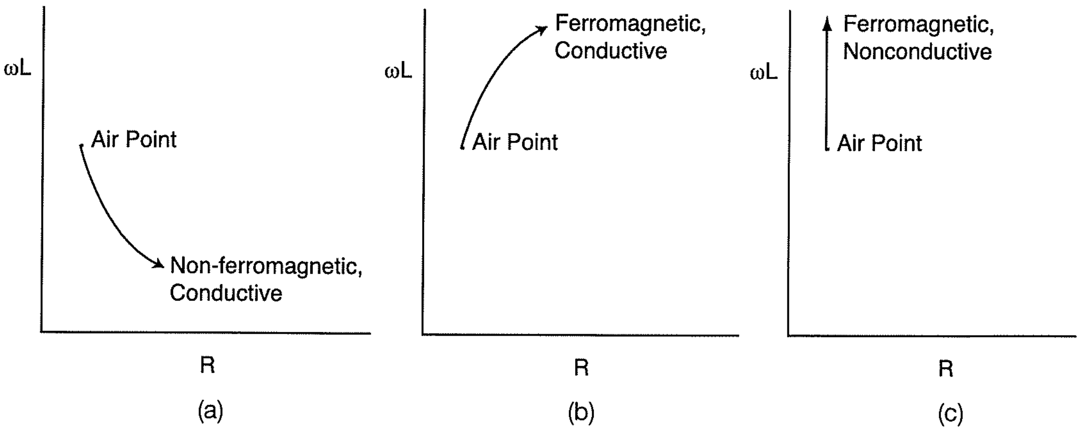


FIGURE 8-47 Lift-off curves. (a) Nonferromagnetic conductive specimen. (b) Ferromagnetic, conductive specimen. (c) Ferromagnetic nonconductive specimen.

off and fill factor variations is an important element in most eddy current inspections. Special techniques, fixtures, and instrument circuit designs have been developed to suppress these signals. When performing lift-off and fill factor applications, it is best to operate at high test frequencies. This reduces penetration into the test material, thus lessening the effects of material variables on test results.

Edge Effect

Just as increasing the spacing between a surface coil and conductive material causes a lift-off curve, moving the coil toward the edge of the material will cause an edge effect trace (Figure 8-48). This results from compression of the field and then reduction of current density as the coil is moved off the edge of the test specimen.

If the eddy current field simultaneously intercepts a discontinuity while approaching the edge, the two conditions will produce a combined response, rather than separate edge and discontinuity indications. Thus, the discontinuity may not be detected. The

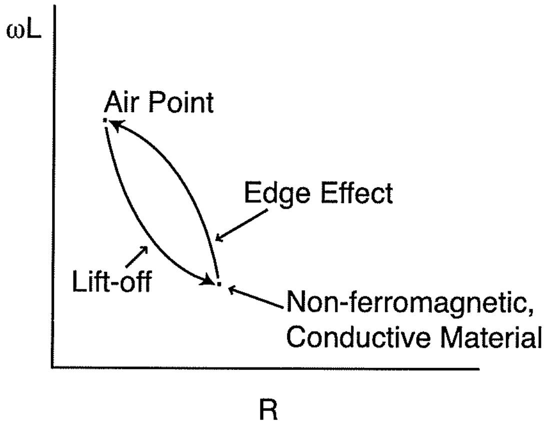


FIGURE 8-48 Edge effect versus lift-off.

problem can be eliminated by scanning the coil parallel to the material edge at a constant distance from the edge to first establish a uniform edge effect indication. Interception of a discontinuity will then cause an additional response. Edge effect is intensified by the wider eddy current fields developed by large diameter coils and lower test frequencies. Use of smaller diameter coils reduces edge effect; use of shielded coils virtually eliminates it.

Surface Coil Impedance Curves for Material and Performance Variables

Although there are some differences among the signals obtained from surface coils, internal coils, and encircling coils, surface coils are ideal for demonstration purposes. This is because they are easily manipulated, are employed for a wide variety of applications, and retain good coupling to the test specimen when their diameter is varied (in contrast to internal and encircling coils, whose diameter must depend on the diameter of the test specimen). The following sections show a variety of material and performance variables using hand-held surface coils.

Conductivity Variation

Figure 8-49a shows the so-called conductivity curve, the locus of the end points of the lift-off curves for all nonferromagnetic, conductive materials. In order for materials to be positioned on this curve, their thickness must be effectively infinite relative to electromagnetic penetration. The counterclockwise extreme of the conductivity curve represents zero conductivity; the clockwise extreme of the curve represents infinite conductivity. Varying test frequency shifts the impedance points for materials of different conductivities along the conductivity curve on the normalized impedance plane. At higher frequency (Figure 8-49b), the impedance points for the various conductivities advance clockwise along the curve, with lower conductivity materials spreading apart while higher conductivity materials compress at the bottom end of the curve. Conversely, at lower frequency (Figure 8-49c), the impedance points move counterclockwise, with higher conductivity materials spreading apart while the lower conductivity materials become compressed at the top end of the curve. Thus, higher frequencies provide greater separation for conductivity tests on lower conductivity materials, while lower frequencies provide greater separation for conductivity tests for high-conductivity materials.

Frequency adjustment also helps separate the lift-off and conductivity variables during conductivity tests, as shown in Figure 8-50. At low frequencies, lift-off curves for low-conductivity materials are almost parallel to the conductivity curve. As frequency is increased, the operating point advances clockwise along the conductivity curve, increasing the angle between the lift-off curve and conductivity curve. Optimum separation is achieved near the so-called "knee" of the conductivity curve. Advancing beyond the knee will lengthen the lift-off curve, increasing sensitivity to lift-off noise caused by probe wobble.

From the standpoint of eddy current testing, conductivity is a material's most important variable. A material must be conductive in order for it to be tested by eddy currents. In addition, conductivity affects test performance. There are two groups of factors that can cause a material's conductivity to vary: those that result in useful applications and those that can sabotage the test process. Factors affecting conductivity variations that can result in test applications include the following:

1. *Variations in chemical composition.* The various metallic elements and alloys can be sorted as long as none of the materials have overlapping conductivities. Certain ranges of copper alloys have overlapping conductivities, for example, and therefore could not be sorted.

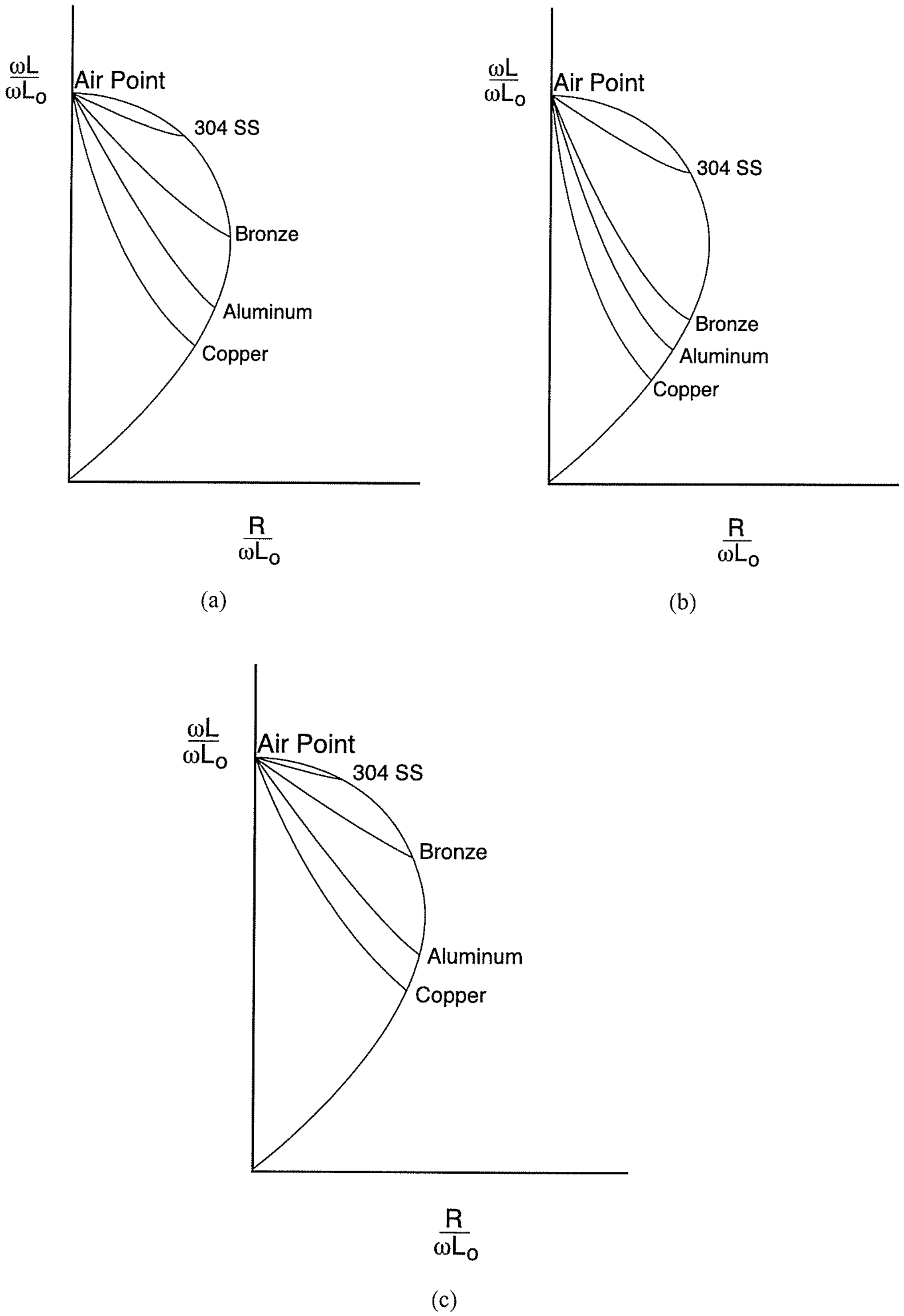


FIGURE 8-49 Conductivity curve: (a) medium frequency, (b) high frequency, (c) low frequency.

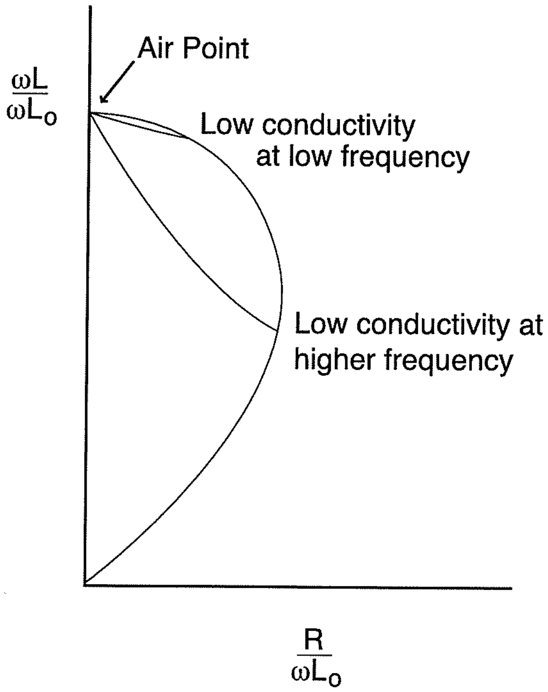


FIGURE 8-50 Effect of frequency on separating signals.

2. *Mechanical processing.* Cold working affects lattice structure, causing minor conductivity changes.
3. *Thermal processing.* Heat treatment causes hardness changes that are detectable as conductivity variations. Because of this, eddy current testing can be used to some extent as a process control for heat treatment.
4. *Variations in thickness of plating or cladding* are a combination of both conductivity and dimensional variables.

Factors affecting conductivity that can negatively impact test performance include:

1. *Material temperature.* As material temperature increases, conductivity decreases. Variations in temperature can be caused by environment, materials processing, and eddy currents themselves. Care must be taken that material temperature does not vary during testing and that reference standards are the same temperature as the test material. Temperature variation during testing can cause the display dot to drift away from the balance point.
2. *Unrelieved residual stress* causes unpredictable conductivity variations. Thus, it is an undesirable variable.

Ferromagnetic Materials

It follows that the effects of ferromagnetic test materials on the impedance of the coil will be similar to those obtained when a ferromagnetic core is used to enhance the flux density of an eddy current surface coil. The coil's alternating electromagnetic field causes the domains of the ferromagnetic material to rotate so that its poles alternate along with the coil, the two fields combining into a field of increased flux density. This increase in primary coil flux density (Φ_P) causes an increase in back voltage, which results in an increase in inductive reactance. The impedance point therefore moves upward on the impedance plane.

The difference between a coil with a ferromagnetic core versus bringing the coil into contact with ferromagnetic test material is that since the core is a permanent part of the coil assembly, it causes the air point to be positioned higher on the inductive reactance axis. Conversely, proximity between the coil and ferromagnetic test material can be varied, with the result that the air point remains lower and inductive reactance increases only as the coil is brought closer to the test material. Moreover, the coil can be brought into proximity to ferromagnetic test materials of various conductivities. Thus, there is theoretically a conductivity curve for every permeability value.

Discontinuity Signal Display

One of the most important applications of eddy current testing is detection and evaluation of cracks and other discontinuities. The impedance plane responds to discontinuities depending on the density and phase lag of interrupted eddy current circulation. Displayed signal amplitude depends on the total quantity of deflected electrons, whose density is decreasing exponentially with increased depth. Displayed phase lag depends on the weighted average of the phase lags of all deflected electrons, whose phase lag is increasing linearly with increased depth. In fact, since a discontinuity of any size will possess some degree of thickness, it will interrupt eddy currents over a *range* of current densities and phase lags, depending on the dimensions, shape, and orientation of the discontinuity.

Table 8.2 shows eddy current density and phase lag at one, two, and three standard depths of penetration. The table indicates that displayed phase lag represents a round trip of lag time from the material surface to the discontinuity and back again to the surface. To obtain meaningful depth information, the skin depth formula must first be employed so that actual depth values can be assigned to 1δ, 2δ, and 3δ.

Subsurface Discontinuities

Assuming that material thickness exceeds five skin depths and that a large-diameter coil is used, theory states that the display of a series of fixed-size voids (see Figure 8-51a) would perform as indicated in Table 8-2 as their depth from the surface varies and produce the display shown in Figure 8-51b.

The lift-off signal represents the test material surface and serves as the 0° reference. Since a so-called "surface void" must necessarily penetrate the surface, it will deflect eddy currents with a phase lag greater than 0°, with it's signal exhibiting some rotation clockwise from the lift-off signal. Similarly, subsurface voids cannot exist only at depths 1δ, 2δ, and 3δ, as indicated in Table 8-2; the voids must have some finite thickness and

TABLE 8-2 Eddy Current Density and Phase Lag for Subsurface Discontinuities

Discontinuity depth	Current density	Phase lag in Material	Phase lag on display
Surface	100.0 %	0.0°	0.0°
1δ	36.8%	57.3°	114.6°
2δ	13.5%	114.6°	229.2°
3δ	5.0%	171.9°	343.8°

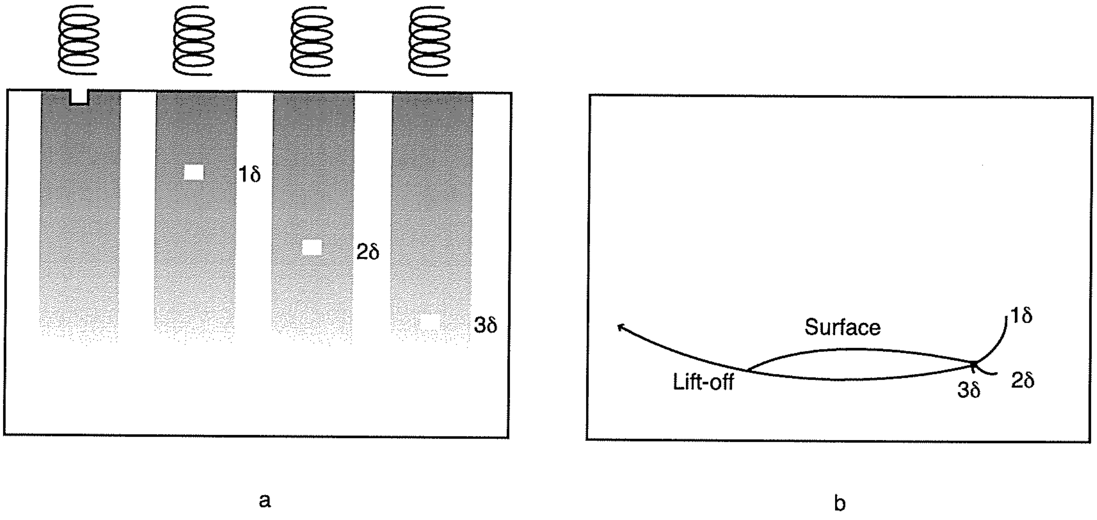


FIGURE 8-51 Subsurface discontinuities: (a) variation in void depth from surface, (b) signal display for voids of different depths.

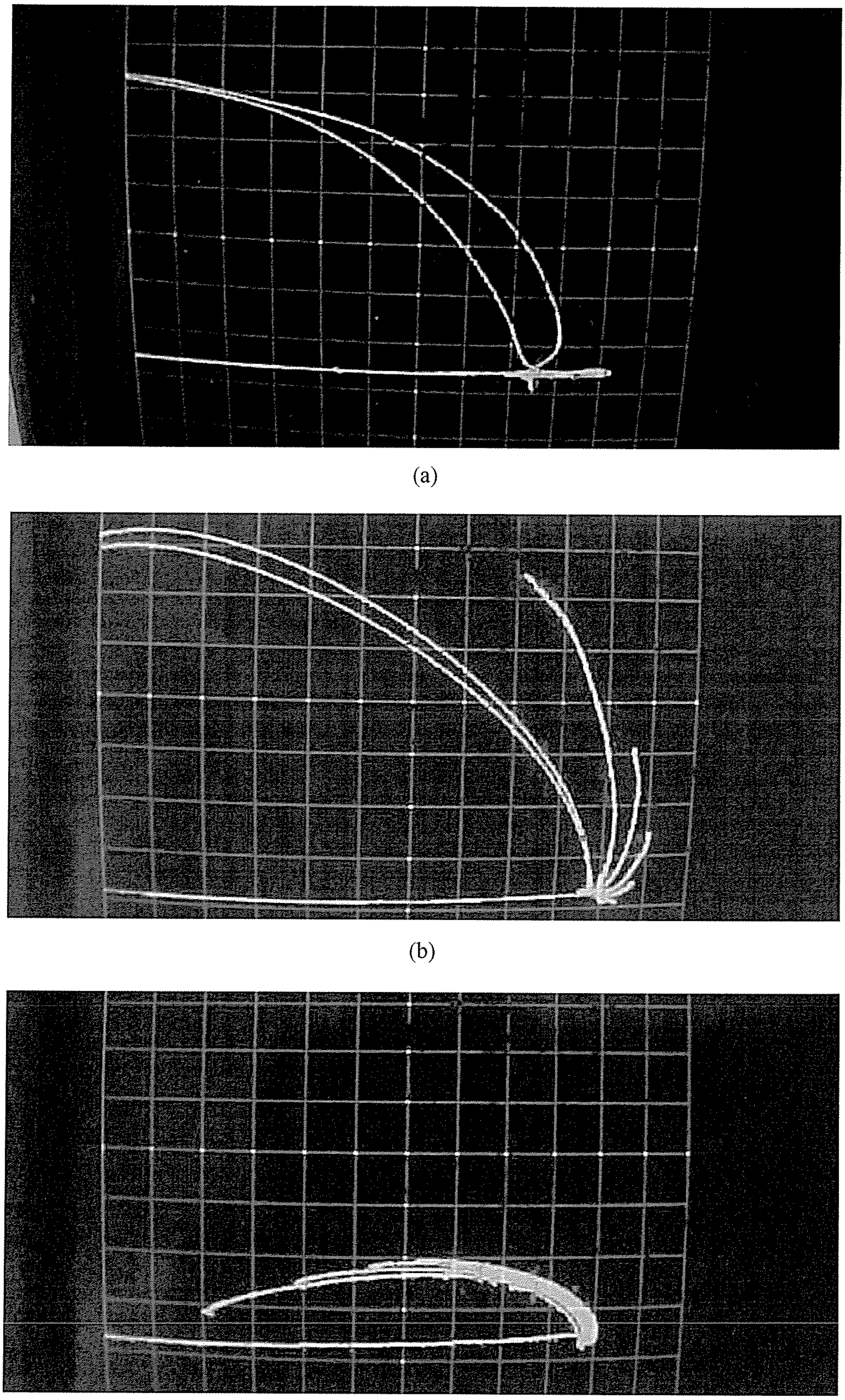
extend a measurable amount above and/or below the stated depths, with a consequent variation in displayed phase lag.

Changing the frequency affects penetration, sensitivity, and resolution. Figure 8-52 compares display of a series of nine subsurface voids at 300 KHz, 50 KHz, and 1 KHz. At 300 KHz, penetration is just adequate to display the top three subsurface voids well separated at approximately 1δ, 2δ, and 3δ. As frequency is decreased, the signals rotate counterclockwise on the display. Thus, at 50 KHz, deeper voids are displayed as penetration increases. Finally, at 1 KHz, nine voids are now only a small portion of one skin depth, with their signals virtually superimposed and lower amplitude. Penetration has been enhanced at the cost of resolution and sensitivity.

Surface-Breaking Discontinuities

The behavior of surface-breaking discontinuities is more complicated. The key to understanding the difference in the display pattern between a series of subsurface discontinuities of increasing depths and a series of surface-breaking discontinuities of increasing depth is, of course, to consider the effect of each on skin effect and phase lag. The subsurface series represents a void of a *fixed volume* whose position is being shifted down to locations of decreased current density and increased phase lag; the surface series represents a void whose *volume is expanding* into locations of decreased current density and increased phase lag. Thus, in that the surface void disturbs fewer additional electrons each time its depth increases by a fixed amount, its signal amplitude increases by progressively smaller amounts. This likewise causes the weighted average of deflected electrons to similarly increase by smaller amounts, resulting in displayed signal phase correspondingly increasing by progressively smaller amounts.

As with subsurface discontinuities, changes in frequency affect penetration, sensitivity, and resolution. Figure 8-53 compares the behavior of the surface-breaking voids in a 304 stainless steel plate at 100 KHz, 10 KHz, and 1 KHz. At 100 KHz, the eddy currents are concentrated on the surface, giving good resolution of the shallowest void, but there is insufficient penetration to resolve the deeper voids. As frequency decreases, penetration is gained at the expense of surface sensitivity. At 10 KHz, there is sufficient density dis-

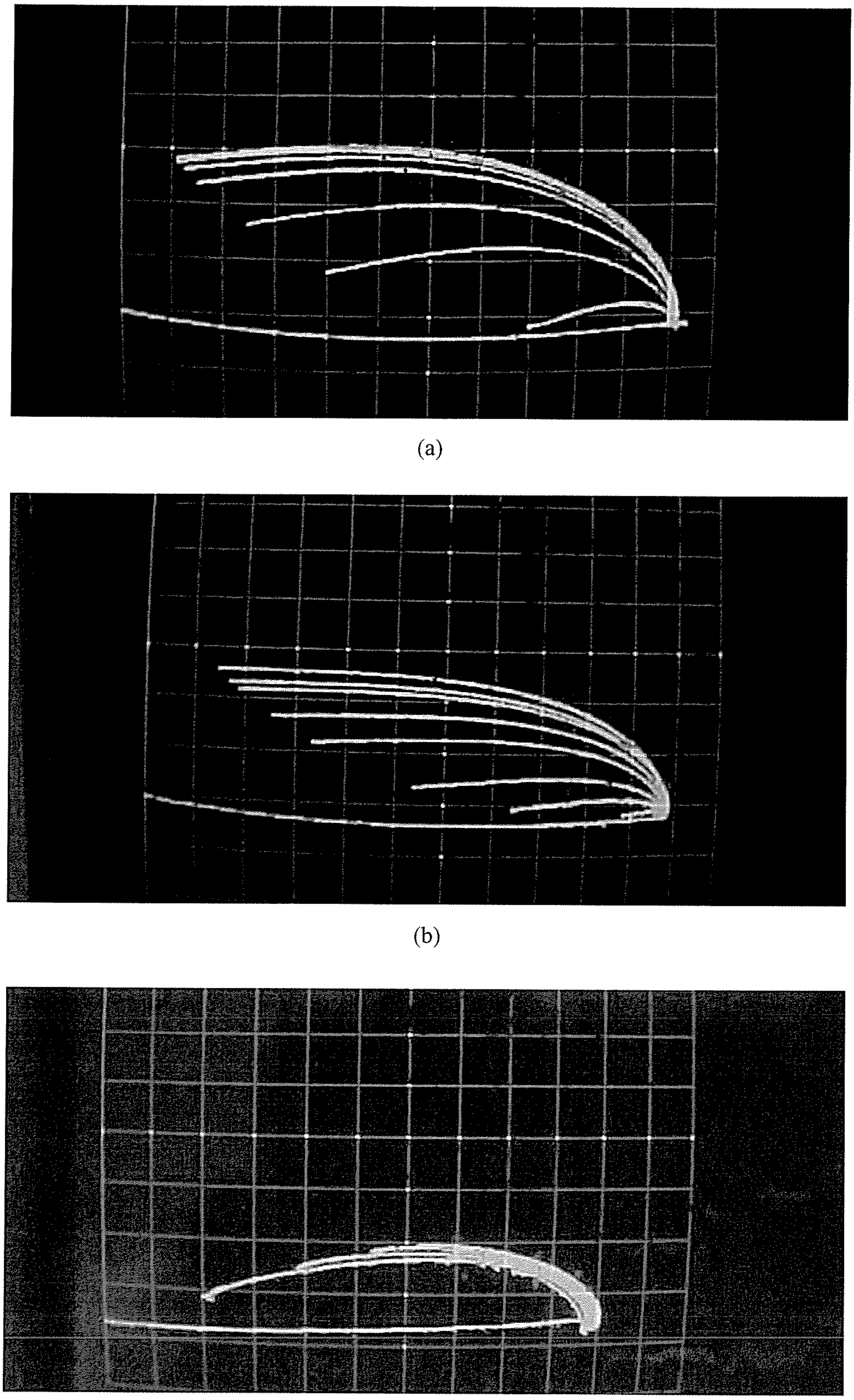


(a)

(b)

(c)

FIGURE 8-52 Subsurface voids at different frequencies: (a) 300 kHz, (b) 50 kHz, (c) 1 kHz.



(a)

(b)

(c)

FIGURE 8-53 Surface-breaking discontinuities: (a) 100 kHz, (b) 10 kHz, (c) 1 kHz.

tribution to obtain adequately resolved signals from the shallowest void as well as the deepest. At 1 KHz, decreased surface sensitivity and phase rotation virtually obscure the signal from the shallowest void.

Shape of the Eddy Current Field

Terms such as "skin depth" and "effective depth of penetration" tend to imply that a decrease in current density and phase lag occur only in the downward direction in the test material. However, the coil's flux, which develops the eddy currents, extends in all directions away from the coil. Therefore, the eddy current field is necessarily somewhat ring-shaped, as shown by the field of the surface coil in Figure 8-54a, with current density and phase lag varying laterally as well as downward, indicated by progression from black through increasingly lighter shades of gray in the cross-sectional view of Figure 8-54b. These field properties become obvious when one examines the signal produced by a surface-breaking discontinuity (Figure 8-54c). Close examination shows that the trace initially proceeds vertically, then curves increasingly toward the left, indicating an initially high phase lag that then decreases as the coil approaches the discontinuity.

Display of Discontinuity Orientation

Figure 8-55a shows a portion of an aluminum bar with machined notches at angles decreasing in 10° increments from 90° to 10°. Figure 8-55b shows how phase lag can be used to indicate the varying orientation of these surface-breaking discontinuities. As discontinuity orientation tilts away from the perpendicular, an increasingly open series of loops is traced on the display, indicating a progressively less rapid variation of phase lag. It is also possible to state the direction in which the discontinuity is leaning. If the signal trace advances clockwise as the coil approaches the discontinuity, then the field is being interrupted in an area of lower phase lag, signifying that the discontinuity is being intercepted where it breaks the surface. However, if the trace advances counterclockwise, greater phase lag is initially indicated, the result of the discontinuity being intercepted deeper into the material.

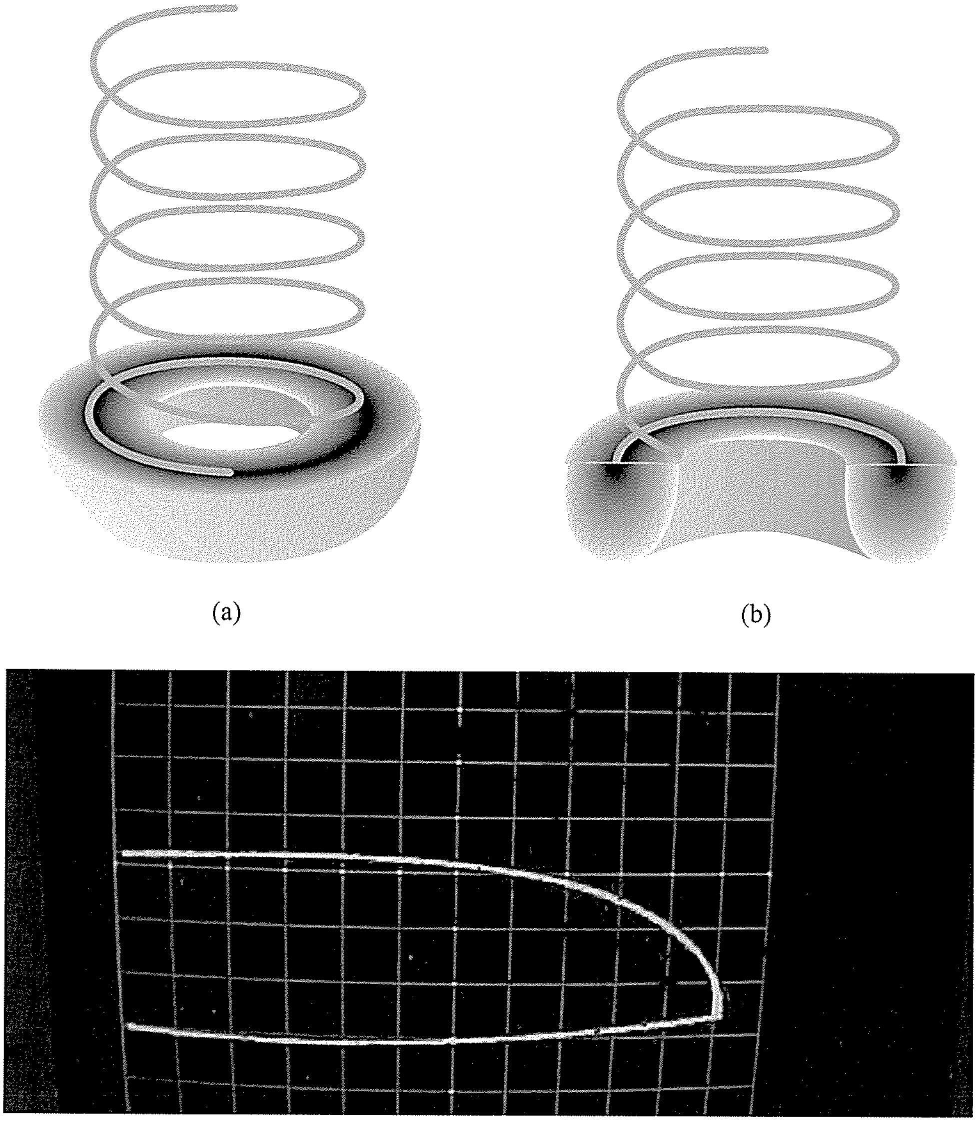
Enhancing Signal Display

In addition to the instrument gain control, which adjusts amplification of bridge output, most impedance plane display instruments provide capability to adjust the ratio of amplification for horizontal versus vertical display of test signals. This feature can be especially useful for improving signal resolution. Figure 8-56a shows a display of surface-breaking notches of increasing depth, with the inevitable reduction of phase separation as notch depth increases. In Figure 8-56b, the vertical amplification has been increased at the expense of the horizontal, stretching apart the signals for improved resolution. The enhancement is accompanied by a corresponding amount of signal distortion, as indicated by the increased curvature of the lift-off trace. The user should be careful to return the horizontal/vertical display amplification to normal settings after completing the application, to preclude undesired distortion during subsequent tests.

Thickness Variation

Thickness variations exhibit the same display behavior as subsurface discontinuities, except that they represent an infinite-size void whose depth is increasing. The phase rotation pattern is the same, but the signal amplitude is greater. Figure 8-57a shows the lift-off curves for a series of aluminum samples of increasing thickness. When the end points of the lift-off curves are joined, a spiral curve is produced. Such a spiral would be traced if the coil were drawn along the length of a wedge covering the same thickness range.

Frequency variation also follows the same pattern as for subsurface discontinuities.

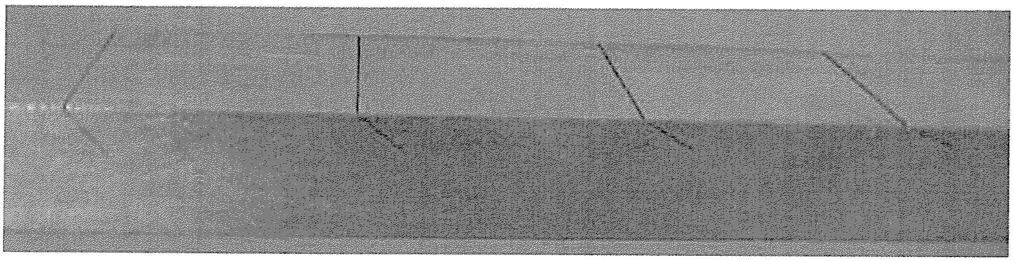


(a) (b)

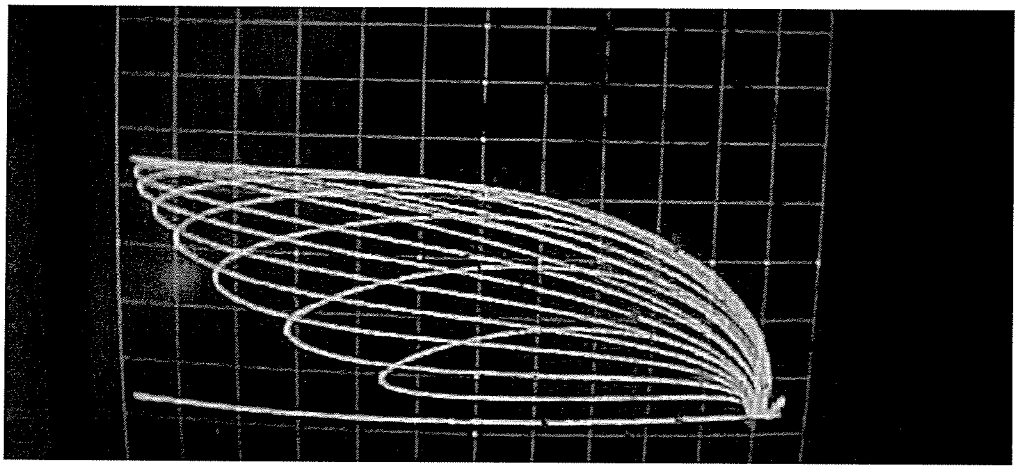
(c)

FIGURE 8-54 Effect of field shape on signal display. (a) Eddy current field shape for surface coil. (b) Cross section of eddy current field. (c) Signal for coil approaching surface-breaking discontinuity.

Decreasing frequency improves penetration and rotates signals from greater depth in a counterclockwise direction. Increasing frequency reduces penetration, but improves resolution of signals from thinner materials by rotating the signals clockwise. These effects of frequency variation are illustrated using a series of eleven aluminum steps ranging in thickness from 0.012″ to 0.100″. In Figure 8-57b, at a frequency of 10 KHz, the thinner steps are well separated, but penetration is only sufficient to resolve the first nine steps. When frequency is reduced to 2 KHz (Figure 8-57d), penetration is increased to the point



(a)



(b)

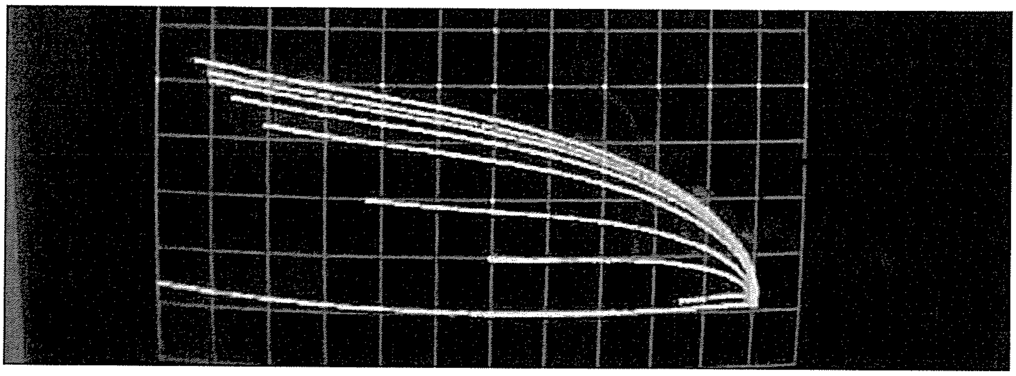
FIGURE 8-55 Display of varying discontinuity orientations. (a) Bar with discontinuities of varying orientations. (b) Signal variation as orientation is varied.

where all eleven steps are resolved, but the reduction in frequency has reduced displayed separation of the thinner steps.

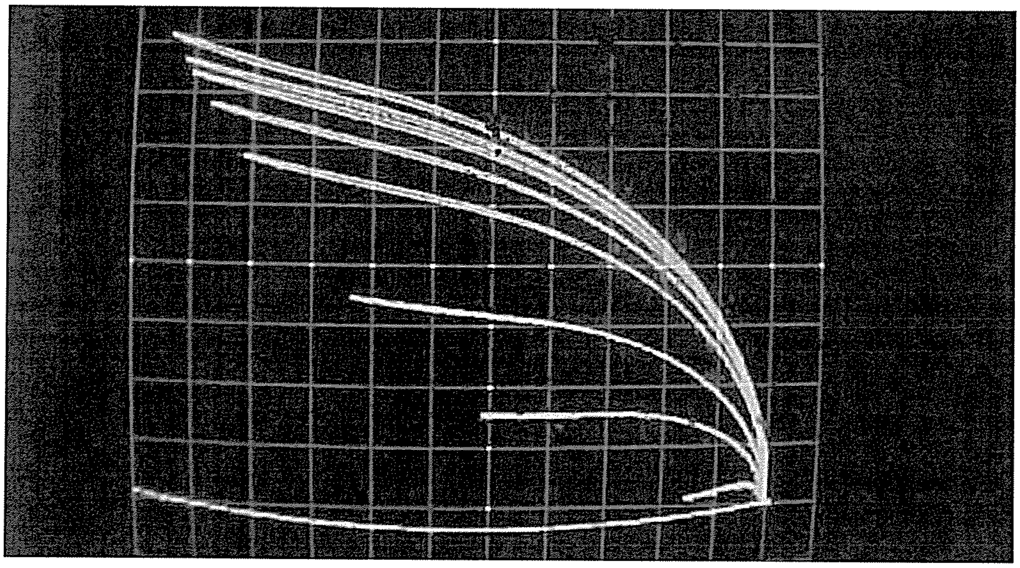
Plating and Cladding

Variation in thickness of one conductive nonferromagnetic material bonded over another is shown in Figure 8-58. Figure 8-58a shows how a wedge of high-conductivity material (copper) bonded over low-conductivity material (304 stainless steel) would be displayed. As thickness increases, a spiral advances from the 304 stainless position on the conductivity curve and reaches the copper position on the conductivity curve when the thickness of the copper becomes effectively infinite and the effects of the 304 stainless can no longer be detected. In effect, a thickness curve for the copper has been grafted onto the conductivity curve, with 1δ, 2δ, and 3δ appearing at their usual positions of phase rotation. Figure 8-58b shows that low-conductivity material bonded over high-conductivity causes the thickness spiral to be inverted.

The display for nonferromagnetic (304 stainless steel) material bonded over ferromagnetic (carbon steel) is shown in Figure 8-59. As thickness increases, a curve proceeds from the impedance plane position for carbon steel to the position for 304 stainless on the conductivity curve for nonferromagnetic materials. The illustration shows the display for



(a)



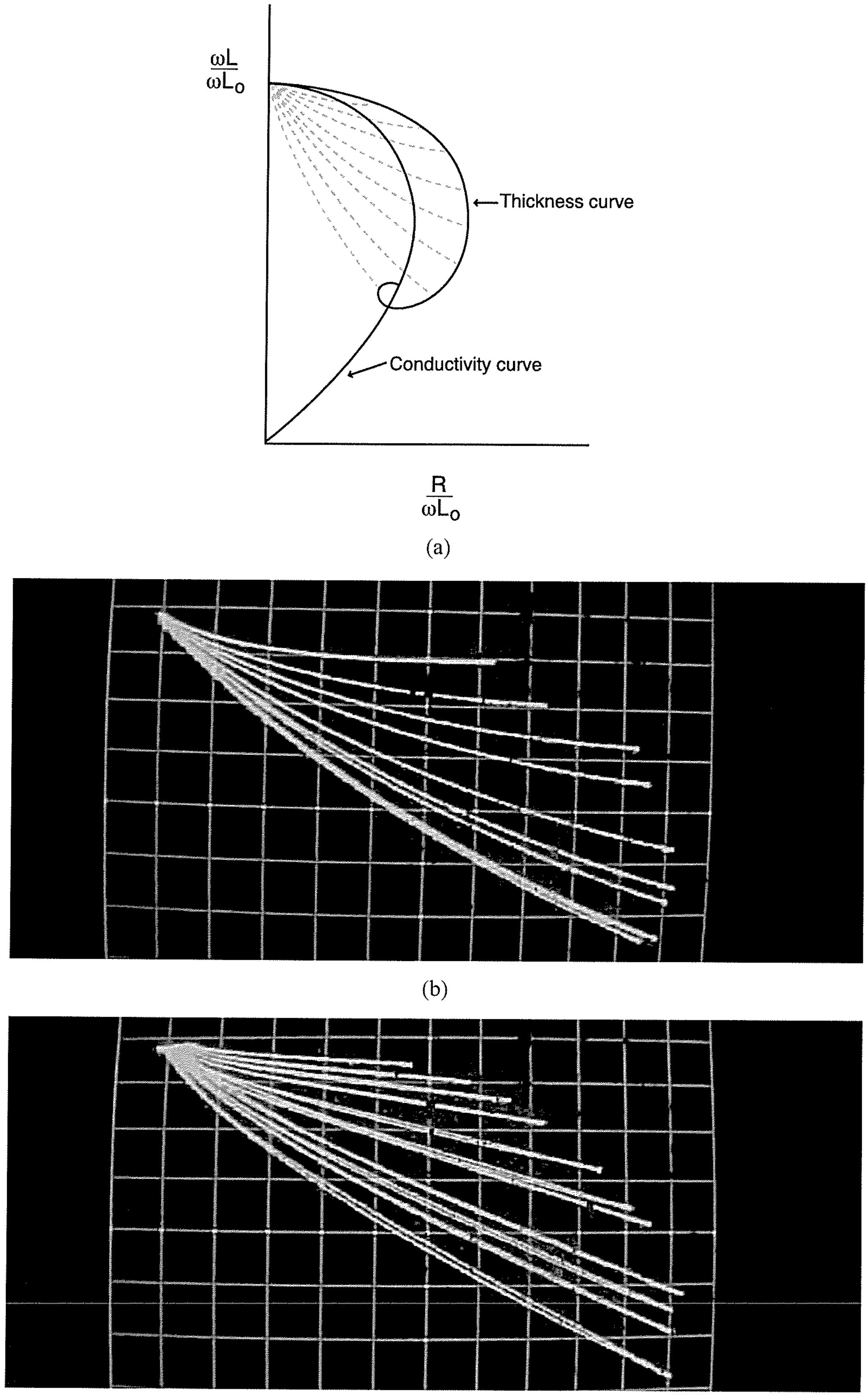
(b)

FIGURE 8-56 Signal enhancement using display amplification. (a) Surface-breaking notches without enhancement. (b) Surface-breaking notches with enhancement.

a wedge of 304 stainless positioned on carbon steel, as well as lift-off curves for various thicknesses of 304 stainless bonded over carbon steel.

Spacing between Conducting Materials

The coil's flux can penetrate multiple layers of conducting material. Therefore, it is possible to use eddy currents to measure thickness of adhesives or air gaps between two metal samples, providing that the combination of conductivity, frequency, and coil diameter provides adequate penetration. Figure 8-60 shows the spacing curve traced for a wedge-shaped air space between two layers of aluminum. As the coil is scanned along the upper metal surface, in the direction of increasing gap thickness, a curve is traced from the point of infinite aluminum thickness on the conductivity curve to the point on the aluminum thickness curve that represents the thickness of the upper metal surface. Frequency must be selected so that the position for the thickness of the upper metal layer is far enough up the thickness spiral for a usefully long spacing curve to be traced.



(a)

(b)

(c)

FIGURE 8-57 Thickness testing. (a) Thickness spiral. (b) Thickness signal display at 10 KHz. (c) Thickness signal display at 2 KHz.

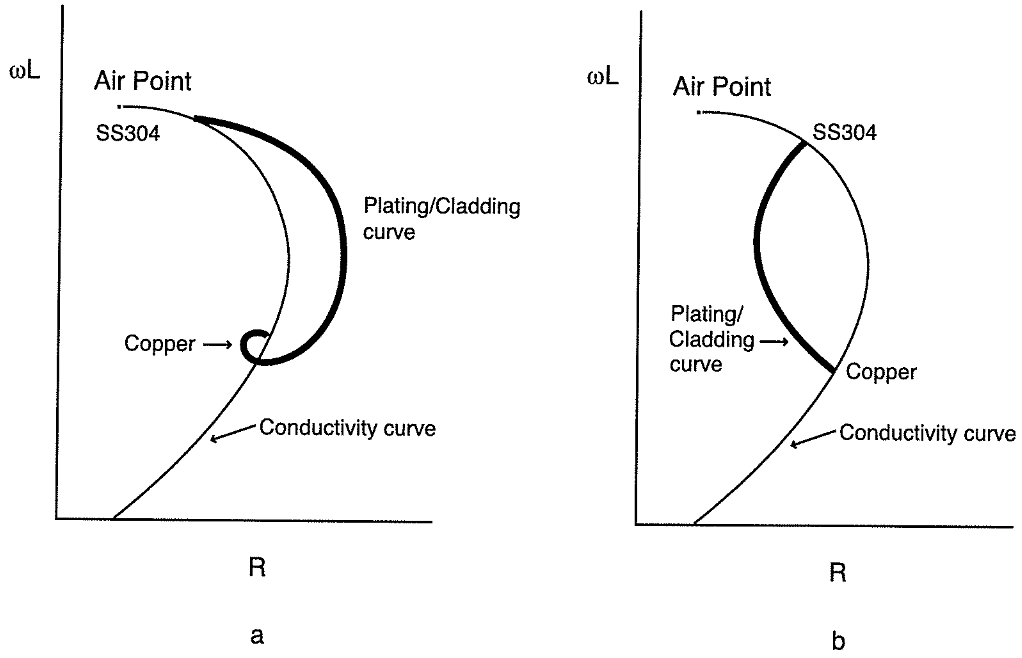


FIGURE 8-58 Thickness of nonferromagnetic plating/cladding over nonferromagnetic base material. (a) High conductivity bonded over low conductivity. (b) Low conductivity bonded over high conductivity.

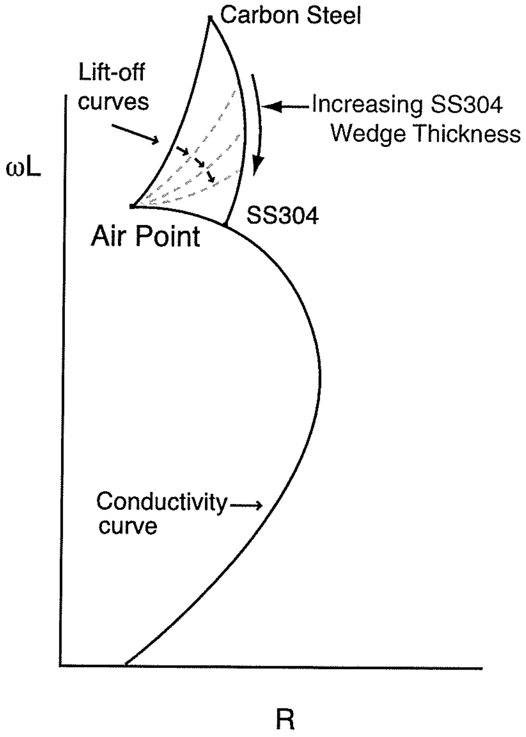


FIGURE 8-59 Thickness of nonferromagnetic plating/cladding over ferromagnetic base material.

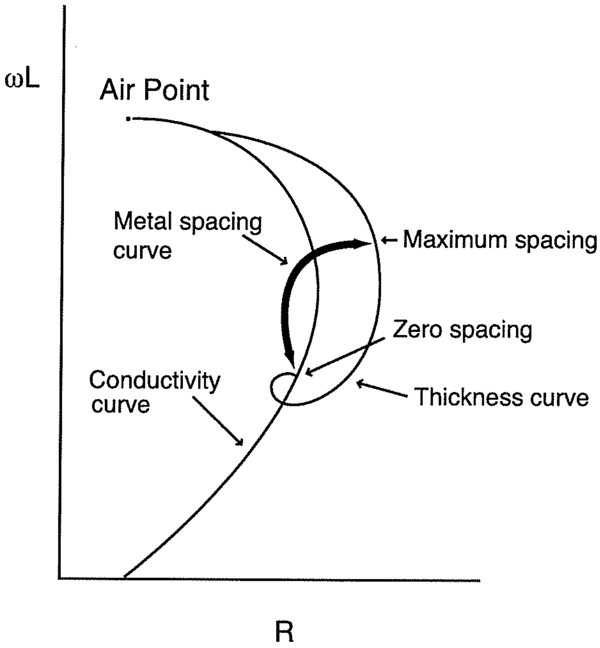


FIGURE 8-60 Metal spacing.

Differential Surface Coil Display

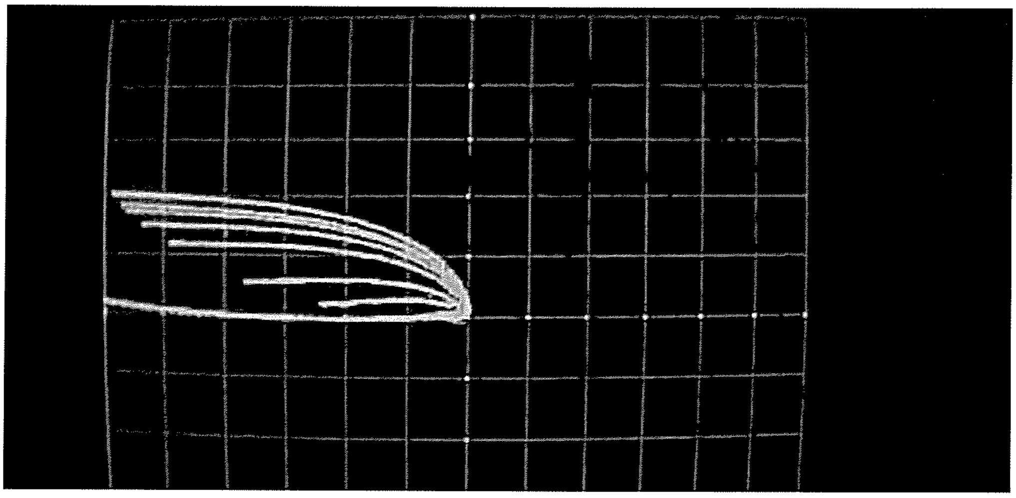
For purposes of convenience and simplicity, all display illustrations in this section have been those of surface coils operating in the absolute mode. Figure 8-61 compares display of absolute (Figure 8-61a) versus differential (Figure 8-61b) surface coil indications for surface-breaking voids of increasing depth. The differential coil pair was oriented so that one coil followed the other as the discontinuities were intercepted. However, if the probe were rotated 90°, so that the coils jointly intercept each discontinuity, the signals would almost completely cancel each other. Thus, while differential coils have the advantage of suppressing unwanted signals such as lift-off noise, the user must be well aware of their characteristics.

Encircling and Internal Coil Display

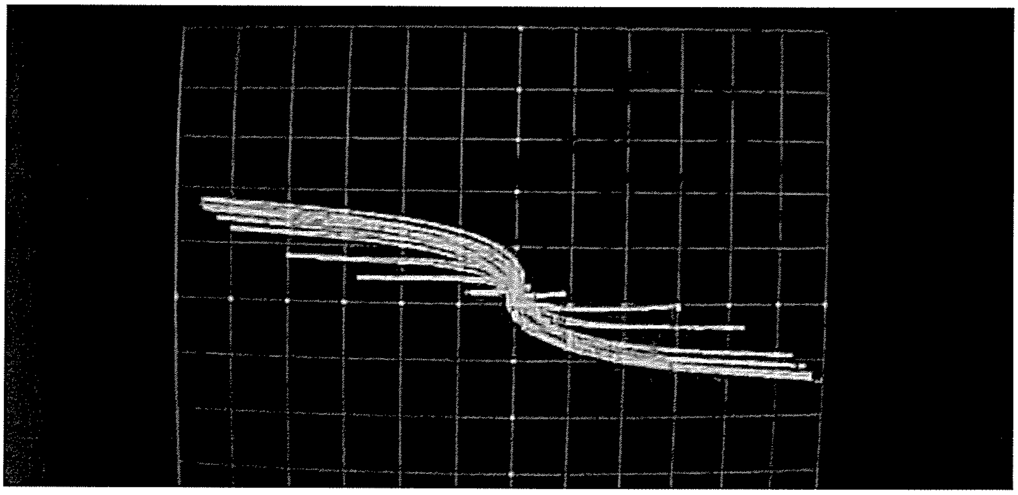
Figure 8-62 shows signal traces from a series of external circumferential grooves on the same tubing standard intercepted by both encircling (Figure 8-62a) and internal (Figure 8-62b) differential coils. The grooves are detected as surface-breaking by the encircling coil and subsurface by the internal coil.

Law of Similarity

In the discussion of conductivity, it was shown that positioning along the comma-shaped impedance curve advances clockwise as conductivity increases. It was also shown that individual conductivity positions shift along the curve as test frequency is varied. In the case of surface coils, for example, similar shifts also occur with changes in permeability and coil diameter. Thus, a given position along the impedance curve depends on a combination of factors. If positioning along the impedance curve can vary with conductivity, frequency, permeability, and coil diameter, the question arises as to what a given curve position actually represents. The answer is that a given position along the curve represents



(a)



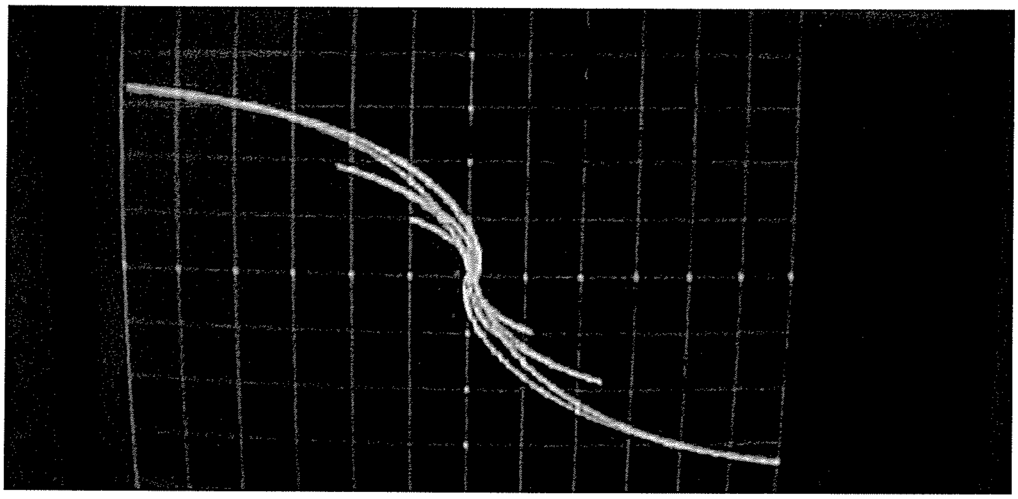
(b)

FIGURE 8-61 Absolute versus differential coil systems. (a) Absolute. (b) Differential.

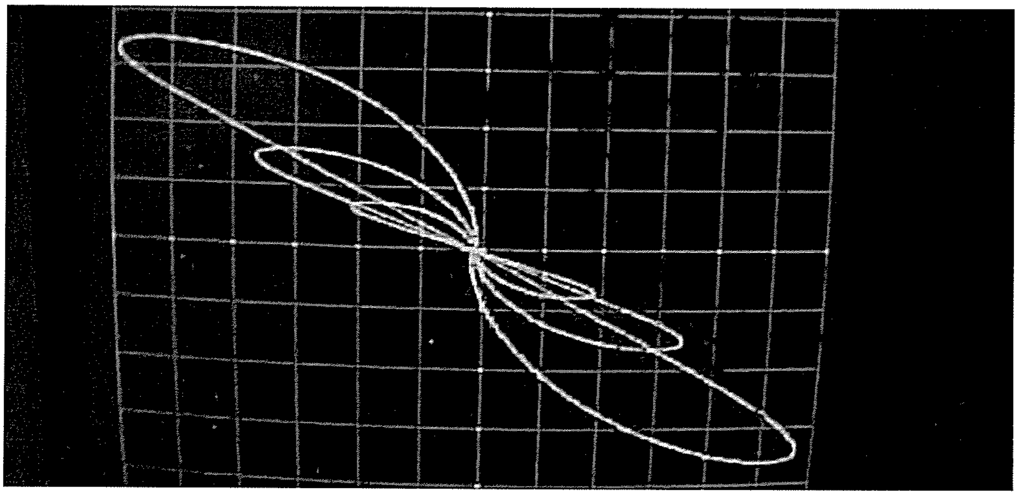
a specific distribution of eddy currents in the test material and that conductivity, frequency, permeability, and coil diameter all affect that distribution. Since distribution of eddy currents affects the major performance criteria—sensitivity, penetration, and resolution—position along the impedance curve largely determines test performance.

Various systems have been devised for assigning reference values for different positions along the impedance curve. The most well-known system is probably the one defined by Foerster for encircling coils enclosing a long bar, the f/f_g ratio. The "f" value represents the frequency at which the test instrument is driving the coil. The f_g value is a mathematically derived reference value known as the *limit frequency,* calculated as follows:

$$f_g = \frac{5.066\,\rho}{\mu_r D^2}$$



(a)



(b)

FIGURE 8-62 Display of signals for encircling and internal differential coils. (a) Encircling coil. (b) Internal coil.

where

f_g = limit frequency (KHz)

ρ = resistivity in microohm-centimeters

μ_r = relative permeability (dimensionless)

D = bar diameter

Ascending f/f_g values are plotted clockwise along the impedance curve, as shown in Figure 8-63. Each position represents a specific eddy current distribution in the test material and, hence, a specific combination of sensitivity, penetration, and resolution. This leads to the concept of the similarity law, which states, in effect, that if test conditions are manipulated to obtain the same f/f_g ratio in two different test objects, performance will be

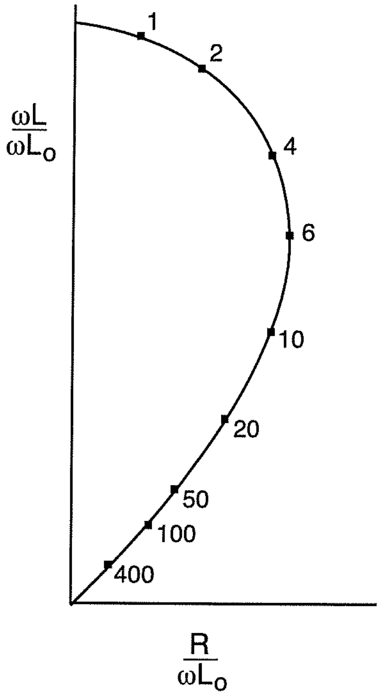


FIGURE 8-63 Impedance curve for f/f_g variations with encircling coil inspecting long bar.

the same for both. For example, a given signal display for an identical discontinuity in both a low-conductivity and a high-conductivity material can be obtained by manipulating test frequency to obtain the same f/f_g ratio for each of them.

8.7 ADVANTAGES AND LIMITATIONS

One of the major advantages of the eddy current method is also one of its most severe limitations. That is, the eddy current method is sensitive to many variables including material conductivity and thickness, size of surface and subsurface discontinuities, thickness of plating or cladding on base metals, spacing between conductive layers, spacing between test coil and test material (lift-off), and permeability variations. However, the major limitation of the eddy current method is that response to these variables is vectorially additive, with the result that when more than one variable is detected by the test coil, all variables combine into a single response that may be difficult to resolve into its separate components. Ability to suppress and render variables separately identifiable is an important element of the user's knowledge. The techniques used to overcome this problem range from relatively simple to complicated and potentially expensive, such as the use of multifrequency instruments.

Additional advantages of the eddy current method include the following:

1. Equipment available for field use has become increasingly portable and lightweight. In addition, many instruments are microprocessor-based, which permits test setups to be saved to memory and test results saved to disk for archiving and analysis.
2. The method is nondestructive. No couplants, powders, or other physical substances

need to be applied to the test material. The only link required between the probe and test material is a magnetic field.

3. Test results are usually instantaneous. As soon as the test coil responds to the test specimen, a qualified user can interpret the results. However, data on a large quantity of test material can be acquired so rapidly, as in the case of in-service tube testing, that it becomes more practical to initially record the data and review it later at a more reasonable pace. Moreover, the use of multifrequency equipment can greatly complicate the amount of data acquired at a given instant and render it overwhelming unless it is recorded and later reviewed as separate elements.
4. Eddy current testing is ideal for "go/no-go" inspections. Audible and visual alarms, triggered by threshold and box gates, as well as gates that can be set to almost any desired shape, are available to automate testing.
5. It is not necessary for the coil assembly to touch the test material. This permits high speed production testing to be done without friction, thus preventing wear of test coils.
6. Eddy current testing is safe; there is no danger from radiation or other such hazards.
7. Material preparation is usually unnecessary and cleanup is not required.

Additional limitations of eddy current testing include the following:

1. The test material must be electrically conductive. However, it is possible to measure the thickness of nonconductive coatings on conducting materials using the lift-off technique.
2. It is difficult to assess subsurface conditions in ferromagnetic materials. Consequently, testing of ferromagnetic materials is limited to detecting surface discontinuities only, unless the material has been magnetically saturated. Magnetic saturation is limited to the testing of geometries that can accommodate saturation coils, primarily encircling coil applications. It is possible to perform inner-diameter inspection of tubing as long as the magnetic field is not so strong as to cause the probe to lock onto the tubing. In addition, magnetically saturated test objects may have to be demagnetized after testing is completed, so that they will not attract ferromagnetic debris.
3. Even on nonferromagnetic materials, the eddy current method has limited penetration, which varies with the material conductivity and test frequency. As a rule, penetration is limited to fractions of an inch in most materials.
4. Inspection speed may have to be limited as a function of test frequency.
5. Much of the eddy current theory is complicated, presenting a challenge to practitioners requiring mastery of the method.

8.8 OTHER ELECTROMAGNETIC TEST TECHNIQUES

In addition to the conventional eddy current testing techniques described above, additional electromagnetic test techniques and equipment have been developed to solve specific applications. Although these techniques cannot be as broadly applied as conventional eddy current testing, they often provide the best solution to a given problem.

8.8.1 Flux Leakage Testing

It was stated earlier that eddy current testing cannot detect subsurface discontinuities in ferromagnetic test material unless the material is magnetically saturated. Saturation, a common technique using encircling coils, is possible but is sometimes inconvenient using internal coils, and is generally impractical using surface coils. Flux leakage testing is used at steel mills and fulfills an important need in the in-service inspection of ferromagnetic tubing.

When a ferromagnetic object that is free of discontinuities is magnetized, an unbroken flux field flows through the object, forming a path between its poles. Flux density decreases toward the outer material surfaces, and a detector of flux leakage would pick up a very weak signal from the surface. However, if the surface is interrupted by a discontinuity, poles are formed at opposite sides of the resulting gap, and flux lines flow externally from the north to south pole. The flux leakage lines are detected by a test probe passing over the discontinuity and a signal is displayed. Disturbance of the material's original flux lines also extends beneath the discontinuity and if the material wall is thin enough, a discontinuity on one wall surface may be detected from the opposite wall. Therefore, it is possible to use internal-type flux leakage probes to detect both inner- and outer-wall discontinuities on tubing.

8.8.2 Remote Field Eddy Current Testing

Remote field eddy current testing is another technique useful for inspection of ferromagnetic tubing. Compared to impedance-type eddy current techniques where detection is limited to surface discontinuities in ferromagnetic materials unless saturation is employed, volumetric inspection of ferromagnetic tubing is possible using remote field testing. This technique responds to material conditions that my not be detectable with flux leakage testing, but this advantage is counterbalanced by possible distortion of the received signal. Although the technique can be used on either ferromagnetic or nonferromagnetic tubing using internal coils, it is not as effective overall as standard eddy current testing, so it is primarily used to obtain penetration in ferromagnetic materials.

Remote field eddy current testing is essentially a geometric variation of familiar send–receive eddy current test techniques, employing a bobbin-wound sending coil that induces eddy currents in the tube wall and a sensor consisting of a single coil or an array. Test frequency is selected such that skin depth is at least as great as tube wall thickness. As usual, eddy current skin effect operates laterally as well as downward from the coil, with eddy currents flowing for some distance in the lateral direction. The eddy currents' secondary flux cancels the coil's primary flux on the inner tube wall near the coil. As distance from the coil increases, this cancellation effect decreases. In the so-called remote field, laterally removed from the sending coil, the sensor can detect phase and amplitude information from the secondary flux developed by the eddy currents. Standard impedance plane display eddy current instruments can be used for remote field inspection. However, the drive voltage for the sending coil must be amplified substantially above the levels normally used for conventional impedance-type eddy current inspection.

8.8.3 Modulation Analysis

Modulation analysis is a production system technique whereby the test material is moved past the coil assembly at a constant high velocity. Impedance amplitude variations are displayed on a strip chart recorder. However, displayed information is selective in that filtration blocks frequencies that contain undesired information from the test material. For example, a high-pass filter would prevent display of the gradual impedance variations characteristic of wall thickness variations, whereas a low-pass filter would block more abrupt impedance variations. Because the amplitude-only display makes it difficult to interpret the type of material variable that causes test signals, material transport speed and filter frequency must be well controlled so that only relevant information is displayed.

8.9 GLOSSARY OF KEY TERMS

Absolute coil technique—An eddy current test in which one arm of the instrument's bridge is connected to a "test coil" that is interfacing with the test material and the opposing arm of the bridge is connected to an electrically similar coil, called a "balance load" or "dummy load," that is remote from the test material.

Alternating current—A current whose direction of flow is periodically reversing.

Atom—The smallest unit of matter; hence, the smallest unit in an electrical conductor. The atom consists of a positively charged nucleus surrounded by one or more "shells" or "orbits" of negatively charged electrons.

Back voltage—Voltage induced into a conductor by means of the varying electromagnetic field of a varying current passing through that conductor.

Bridge circuit—Formally known as a "Wheatstone Bridge," this design is commonly used as the test coil input circuit for eddy current instruments. In this application, it consists of two opposing "arms," each of which contains a coil and is capable of sensing very small impedance differences between the two arms.

Coil in air—A surface coil that is not in proximity to and is therfore unaffected by conducting material.

Conductance—The ability of a particular component to conduct electricity. Conductance depends on a component's conductivity, length, and cross section.

Conductivity—The opposite of resistance, that is, the relative "willingness" of a material to allow the flow of current.

Conductor—A material that contains very few (e.g., one or two) electrons in its outer shell. When there are only a few electrons in the outer orbit, it is easy to cause electrons to move from one atom to the next.

Cross-axis coil—A test coil design in which the coil assembly consists of two coils wound 90° to each other in order to make the coil assembly less directional in sensitivity.

Current—The flow of electrical charges, measured in amperes.

Differential coil technique—An eddy current test in which two opposing arms of the instrument's bridge are each connected to a separate test coil that is interfacing with the test material. Also called the differential self-comparison technique.

Direct current—The flow of electricity in only one direction.

Domains—Miniature magnets consisting of groups of atoms or molecules present within a material's individual grains.

Eddy currents—Circulating electrical currents induced in an isolated conductor by an alternating magnetic field.

Effective depth of penetration—The maximum material depth from which a displayable eddy current signal can be obtained, arbitrarily defined as the depth at which eddy current density has decreased to 5% of the surface eddy current density.

Electricity—The flow of electrons through a conductor from one atom to the next.

Electromagnet—A magnet operating on the principle of electromagnetism, usually consisting of a solenoid coil containing a ferromagnetic core. Electromagnets are distinguished from permanent magnets by the fact that they require electricity in order to operate.

Electromagnetic induction—Relative motion between a magnetic field and a conductor causes a voltage to be induced in that conductor.

Electromagnetism—The phenomenon whereby passage of electrons through a conductor causes a magnetic field to develop concentrically around the conductor, perpendicular to it.

Electron—A negatively charged particle of electrical energy that orbits the atom.

Empty coil—An encircling coil which is not in proximity to and is therfore unaffected by conducting material.

Encircling coil—An eddy current test coil designed so that the test material can pass through its interior wall. It is used primarily for production testing of long, continuous product such as pipe, tube, rod, wire, and bar stock.

External reference coil—A type of absolute coil bridge connection where the bridge's reference coil is sensing a reference standard.

Feed-through coil—See *encircling coil.*

Ferromagnetism—A property whereby materials can become magnetized when their domains have become aligned

Fill factor—The calculated coupling effectiveness between the inner surface of an encircling coil and the outer surface of a specimen enclosed within it or between the outer diameter of an internal coil and the inner surface of a specimen surrounding it.

Flux—See *magnetic flux.*

Flux density—The number of flux lines per unit area perpendicular to the direction of current flow.

Gap probe—See *horseshoe probe.*

Gauss—The unit of measure for flux density. One gauss equals one line of force passing through an area of one square centimeter.

Horseshoe probe—A surface probe configured with the coil wrapped around a horseshoe-shaped permanent magnet, to provide an eddy current field circulating perpendicular to the test surface.

I.D. (inner diameter) coil—See *internal coil.*

Inductance—The property of an electical component, such as an eddy current coil, whereby the component's alternating electromagnetic field induces voltage into the component itself or into a nearby secondary conducting component such as a test specimen.

Inductive reactance—Opposition that induced voltage offers to the alternation of alternating current.

International annealed copper standard (IACS)—A scale used to compare material conductivities with pure, unalloyed, annealed copper at 20°F, as the base value at 100% conductivity. Other materials are assigned percentage values relative to copper.

Impedance—The vector sum of inductive reactance and resistance.

Internal coil—An eddy current test coil designed to pass through the interior walls of tubes and pipes. It is used primarily for in-service inspection of tubing.

Lenz's law—The phenomenon whereby, when a primary circuit induces voltage into a secondary circuit; the direction of current flow in the secondary will be such that the polarity of the secondary flux will be opposite to the primary flux.

Lift-off—The variation in impedance as the distance between a probe coil and a conductor is varied. Lift-off can be a positive effect because it can be used to measure the thickness of nonconductive substances located between the coil and a conductor; but it is often a negative effect because its strong signals can mask the weaker indications of variables that an eddy current examination is intended to measure.

Locus (plural: loci)—A mathematical term indicating a set of points that satisfy a given set of conditions. For eddy current purposes, a set of points that trace a line or curve representing the range of a displayed variable such as conductivity or lift-off.

Magnetic field—A force field radiating from permanent magnets and electromagnets, which decreases in strength inversely as the square of the distance from the poles of the magnet.

Magnetic flux—The lines of force that make up a magnetic field. In the case of an eddy current test coil, which is an electromagnet, the lines of force flow out of one end (pole) of the coil, around the outside of the coil, and back into the other end (pole) of the coil.

Magnetism—The mechanical force of attraction or repulsion that one material can exert upon another.

Normalization—Confirmation to a standard. The impedance plane is normalized to preclude the need to develop separate impedance graphs for each test coil that is used. The vertical axis is normalized by dividing actual inductive reactance of the test coil by inductive reactance of the coil when remote from conductive material. The horizontal axis is normalized by subtracting test coil resistance from total resistance and then dividing the remainder by inductive reactance of the coil when remote from conductive material.

Nucleus—The central portion of the atom, containing protrons, which carry a positive charge and thus balance the negative charge of the orbiting electrons, as well as neutrons, which carry no charge.

Ohm's law—A formula defining the relationship of current, voltage and resistance, as follows:

$$\text{current} = \frac{\text{voltage}}{\text{resistance}}$$

Permanent magnets—Materials that retain their magnetism after they are removed from a magnetic field.

Permeability—The measure of a material's ability to be magnetized; that is, a material's ability to concentrate magnetic flux.

Polarity—The phenomenon whereby opposite ends of a magnet exhibit opposing forces. This is due to the fact that the lines of force flow from the north to the south pole around the outside of a magnet, and from the south to the north pole within the magnet. This causes like poles to repel and unlike poles to attract.

Poles—Nomenclature for the opposite ends of a magnet, one north and one south.

Probe coil—An eddy current test coil, configured in a probe-type housing, designed to be placed in contact with a surface of the test material.

Reflection coil—A coil assembly in which a large outer coil induces primary flux into the test specimen and a pair of stacked inner coils, wound in opposition, sense the secondary flux. The term "reflection" derives from the fact that the inner coils, being wound in opposition, function as electrical mirror images of each other.

Resistance—Opposition to the flow of current. Its unit of measure is the ohm.

Resistivity—The opposition of a material's atoms to the flow of electricity. It is the inverse of conductivity.

Shielded coil—An eddy current surface coil whose turns are surrounded by a cylinder of ferromagnetic material that concentrates the coil's flux field to suppress lateral extension of the field.

Sinusoid—One complete 360° cycle of a sine curve.

Skin depth—See *standard depth of penetration*.

Skin effect—Eddy current density is maximum at the material surface and decreases exponentially with depth. Thus, in thicker materials, eddy current testing operates only on the outer "skin" of the test material. Test sensitivity decreases rapidly with depth, and volumetric tests are possible only on thin specimens.

Standard depth of penetration—The material depth at which eddy current density has decreased to $1/e$ (36.8%) of surface eddy current density.

Self-induction—Induction of voltage into a conductor, such as a test coil, resulting from the coil's own magnetic field expanding and collapsing against the turns of the coil.

Solenoid—A coil of conducting wire whose length substantially exceeds its width.

Surface coil—An eddy current test coil, often configured in a probe-type housing, designed to be placed in contact with a surface of the test material.

Through-transmission—A technique whereby test coils are positioned on opposite sides of the test material, with one coil transmitting and the other coil receiving. This technique increases penetration of eddy currents, but does not provide display of phase information.

Voltage—The polarity applied to electrons, causing current to flow through a conductor. The unit of measure is the volt.

8.10 SUGGESTIONS FOR FURTHER READING

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