respective values increase in opposite directions. The nickel-zinc ferrite cores in Figure 11b were chosen as examples because they have a low conductivity and two different values for permeability. The effect of the increased flux density gives a greater induced voltage in the test coil that in turn raises the impedance. The increase in impedance is in the reactance direction except for the effect of a small amount of energy loss resulting from hysteresis. The nickel-zinc ferrite cores may have an initial permeability of 850, which is high on the permeability line. Usually, practical engineering materials also have an associated electrical conductivity that affects the impedance, as shown for 422 steel and 4340 steel. The relative relationship of the permeability loci lines and the conductivity curves for three materials is shown in Figure 11c.

The vector or phasor values of inductive reactance and resistance for different material conditions yield unique loci or phasor plots on the impedance plane at particular operating frequencies. The phase angle of the impedance vectors will change at different frequencies because the inductive reactance value is a function of inductance and

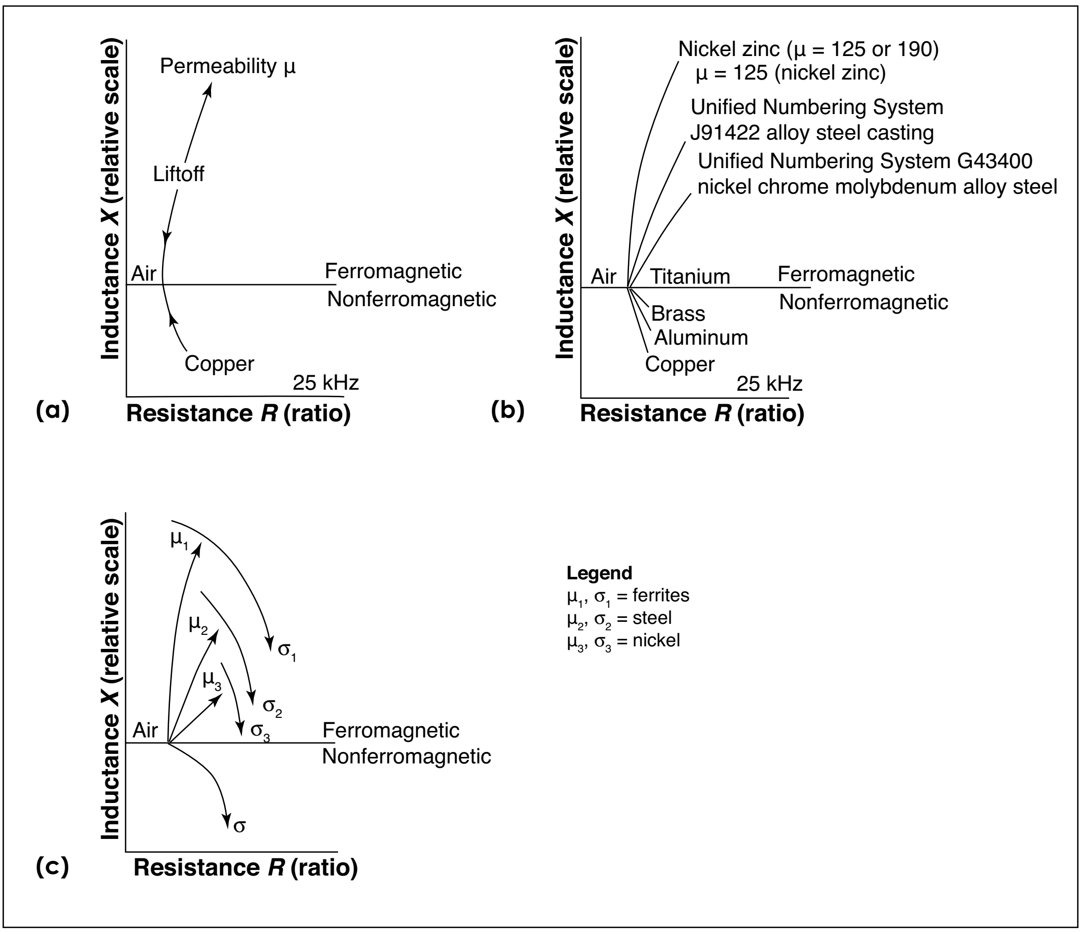


Figure 11. Permeability, liftoff, and conductivity loci on the impedance plane: (a) permeability and liftoff locus; (b) permeability loci for different materials; and (c) loci for permeability (μ) and conductivity (σ).

frequency. Hence vector points may move relative to one another along the conditional loci curves when the operating frequency is changed. This shift in phase is shown in Figure 12 for the conductivity values of nonferromagnetic materials.

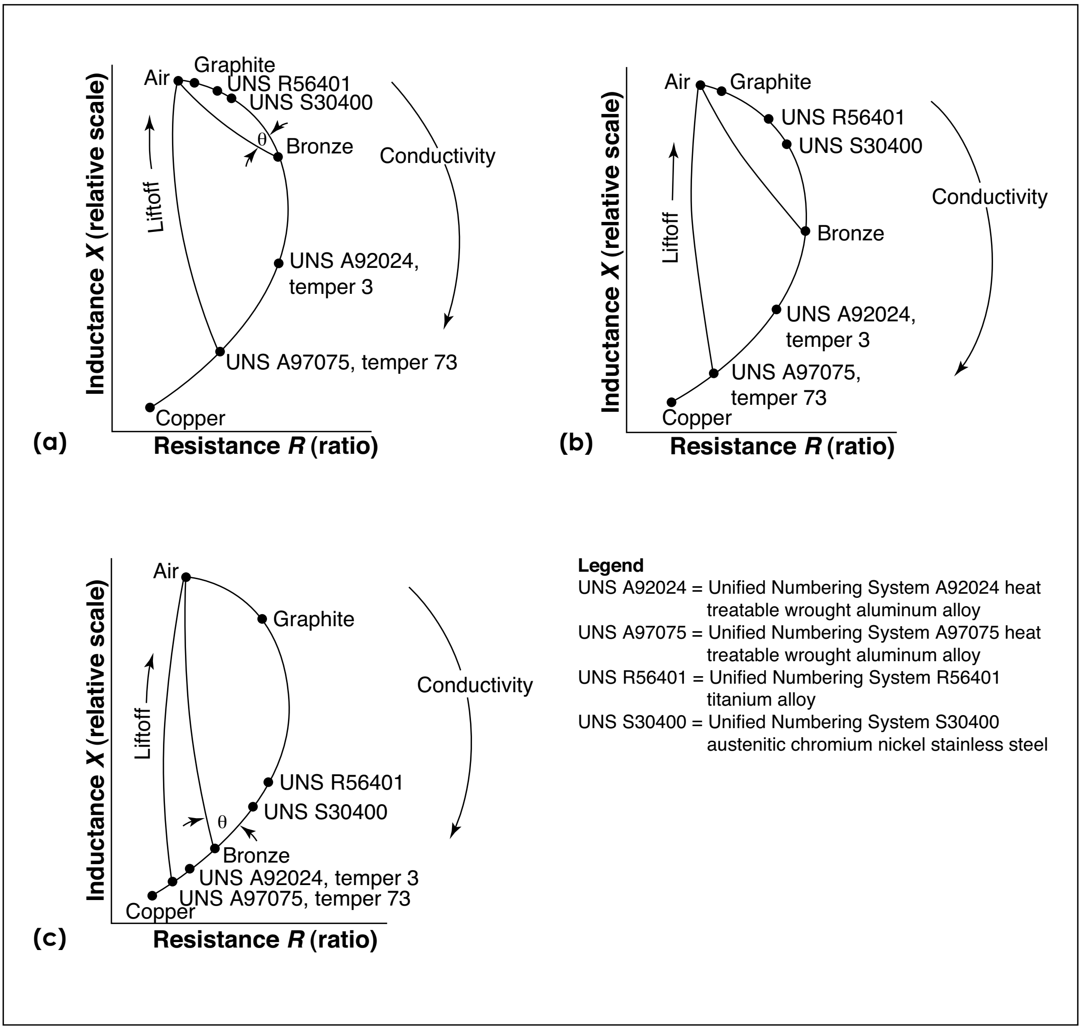


Figure 12. Movement of material points by frequency changes: (a) low frequency (20 kHz); (b) medium frequency (100 kHz); and (c) high frequency (1 MHz).

Similar phase angle changes for the permeability of 4340 steel are shown in Figure 13 as the frequency changes from 75 to 300 kHz. These changes in phase shift at different frequencies do not interfere with impedance-plane analysis, provided that the operator is aware of this factor. In some cases, test results may be improved by changing the frequency to cause phase shifts.

With phase-analysis eddy current instruments, an operator can produce impedance-plane loci plots or curves automatically on a *flying dot* display (see “Vector Point Method” in the following section). Such

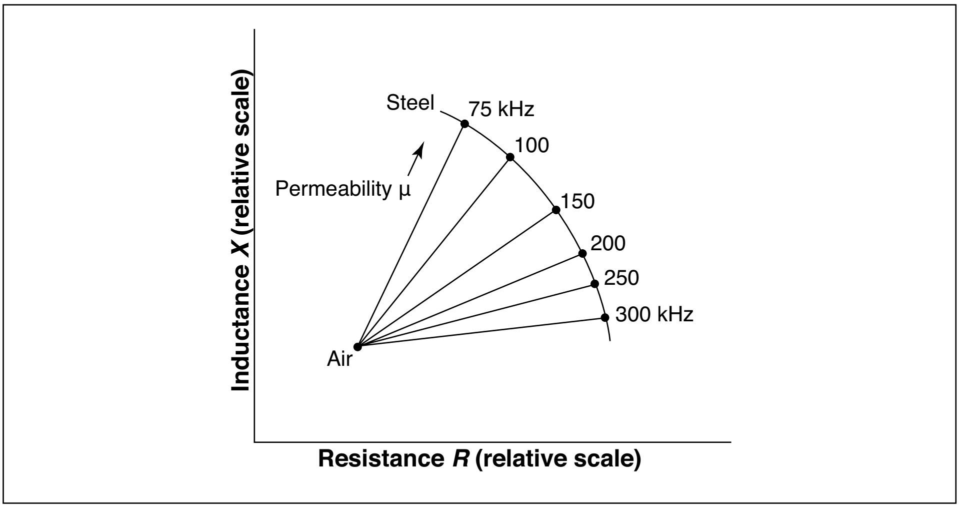


Figure 13. Phase angle changes on the impedance-plane caused by frequency changes.

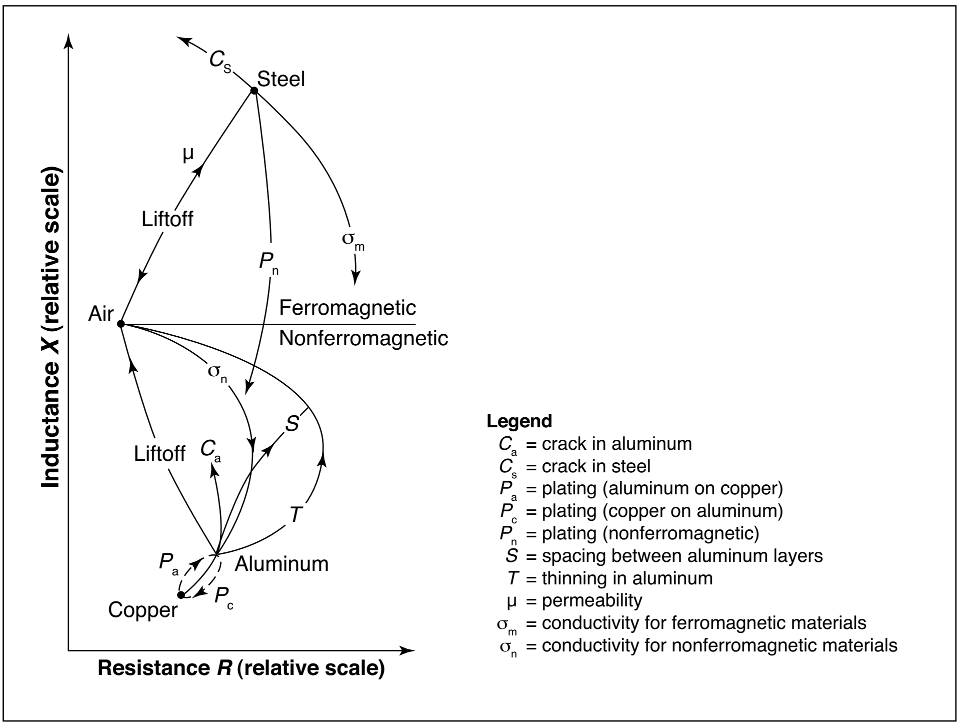


Figure 14. Impedance changes in relation to one another on the impedance plane.

impedance-plane plots can be presented for the following material conditions, as shown in Figure 14:

- Liftoff and edge effects
- Cracks
- Material separation and spacing
- Permeability

- Specimen thinning
- Conductivity
- Plating thickness

Evaluation of these plots shows that ferromagnetic material conditions produce higher values of inductive reactance than values obtained from nonferromagnetic material conditions. Hence, the ferromagnetic domain is in the upper quadrant of the impedance plane, whereas nonferromagnetic materials are in the lower quadrant. The separation of the two domains occurs at the inductive reactance values obtained with the coil removed from the conductor (sample). This is proportional to the value of the coil's self-inductance, L.

Linear material values do not produce linear responses on the impedance-plane loci. When the eddy current probe is balanced on the metal specimen, the loci values for linear material conditions are displayed as follows:

- Ferromagnetic and nonferromagnetic liftoff conditions are displayed logarithmically (in X).
- Ferromagnetic and nonferromagnetic edge effects are displayed logarithmically.
- Ferromagnetic and nonferromagnetic conductivities vary with test frequency.
- Magnetic permeability varies with test frequency.
- Metal thinning varies exponentially.
- Nonferromagnetic plating thickness is displayed logarithmically.
- Material spacing or separation varies exponentially.

In a problem-solving situation, impedance-plane analysis is a useful tool because it improves the ability to detect various conditions and provides a better understanding and interpretation of the eddy current test results.

Digital Displays

Vector Point Method

When a digital display is provided as part of the test equipment, the equipment may be set up to show on the screen the locus of all the points of interest to the technician. Thus, the operator may construct, point by point, the impedance-plane diagram directly on the screen. Digital systems allow the setup of standardization curves constructed from known standards and the automated analysis of signals as compared to these curves. During an actual eddy current test, the impedance of the coil causes a dot, referred to as a flying dot, to appear at some point on the screen. Its position with respect to the impedance-plane diagram tells the technician what is occurring within the test object. Essentially, the point represented by the flying dot describes the in-phase and quadrature components of the signal.

An advantage of using a digital display is its flexibility. For example, the equipment may be set up so that the display is rotated to a position where a change in liftoff would move the dot left or right, while a change in conductivity would move the dot up or down, as shown in Figure 15.

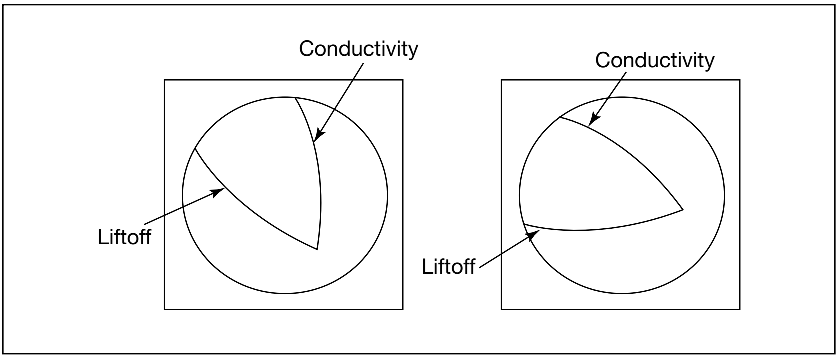


Figure 15. Rotation of the digital display.

Ellipse Display Method

A digital display may also be set up to compare a test object with a reference standard. The ellipse method uses an inspection coil in conjunction with a reference coil. When a standard is placed under the reference coil and the test object is placed under the inspection coil, the display shows the phase relationships between the signals obtained. This comparison between the signals provides indications of the dimension variable and the conductivity variable.

The dimension variable and the conductivity variable are shown on the display by the width of the ellipse and the angle tilt of the axis. Figure 16 shows the appearance of ellipses for dimension and

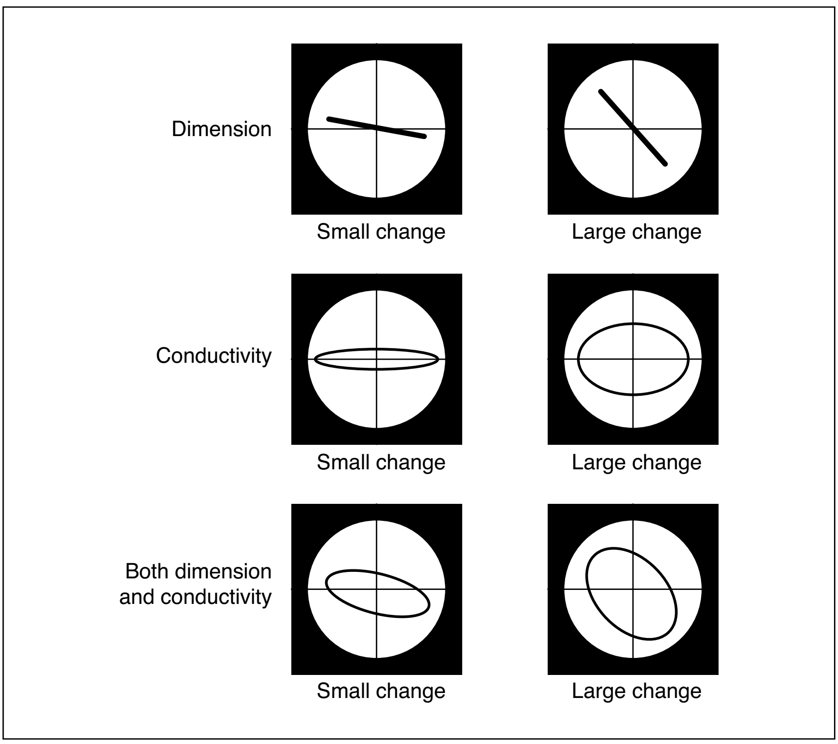
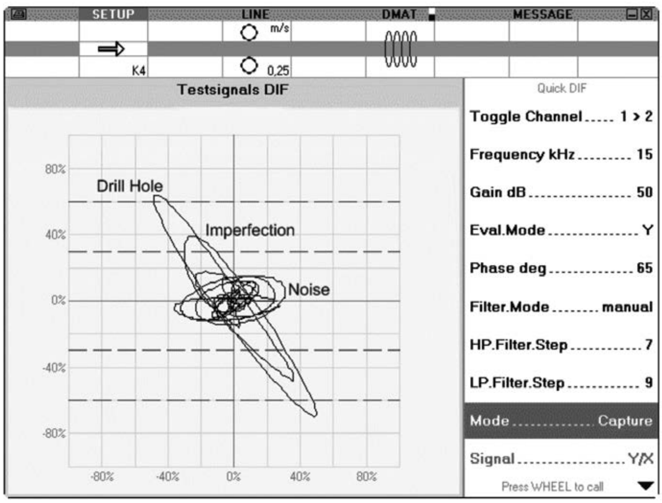
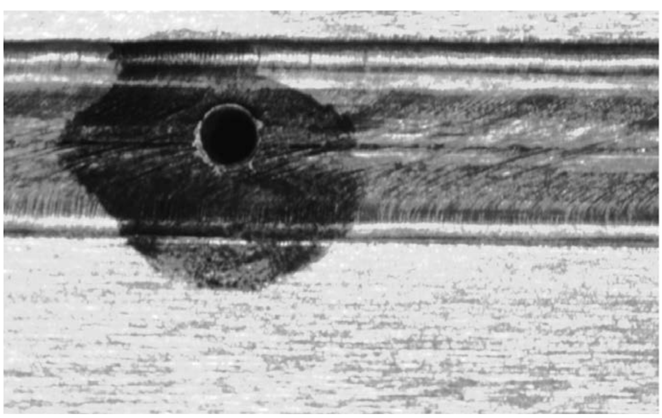


Figure 16. Ellipse displays for dimension and conductivity.

conductivity. Figure 17a shows an X-Y screen display of the single 0.031 in. (0.787 mm) hole drilled through the weld seam of an aluminum tube shown in Figure 17b. The sample was used to optimize instrument settings. A test frequency of 15 kHz provided good phase separation of the noise and discontinuity signals. The indication from an inherent discontinuity in the form of a scratch is labeled on the screen as an imperfection.



(a)



(b)

Figure 17. Electromagnetic test of an artificial discontinuity: (a) X-Y screen display; (b) test sample with drilled hole.

Modulation Analysis

A modulation analysis system, shown schematically in Figure 18, adds a modulating device between the test set and an indicating device or recorder. The modulating device is simply an electronic filter that will pass only certain frequencies. In modulation analysis, a differential coil is used so that two adjacent areas of the test object are compared.

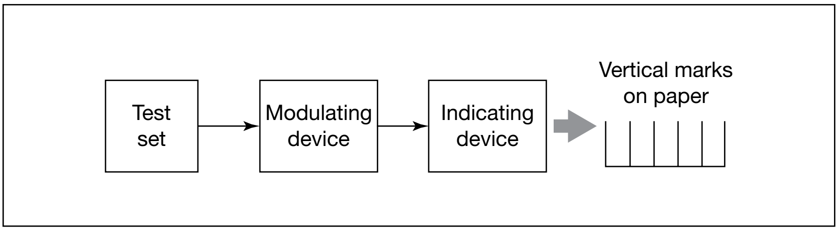


Figure 18. Modulation analysis system.

As the test object passes under or through the coils at a constant rate, various variables being sensed cause the equipment to register a signal. A discontinuity such as a crack will be indicated by a sharp rise in signal, followed immediately by a sharp drop. A dimension change, on the other hand, is most likely to occur gradually. Thus, with the use of either a low-frequency or high-frequency filter, the effect of one variable or the other is eliminated from the readout, as shown in Figure 19.

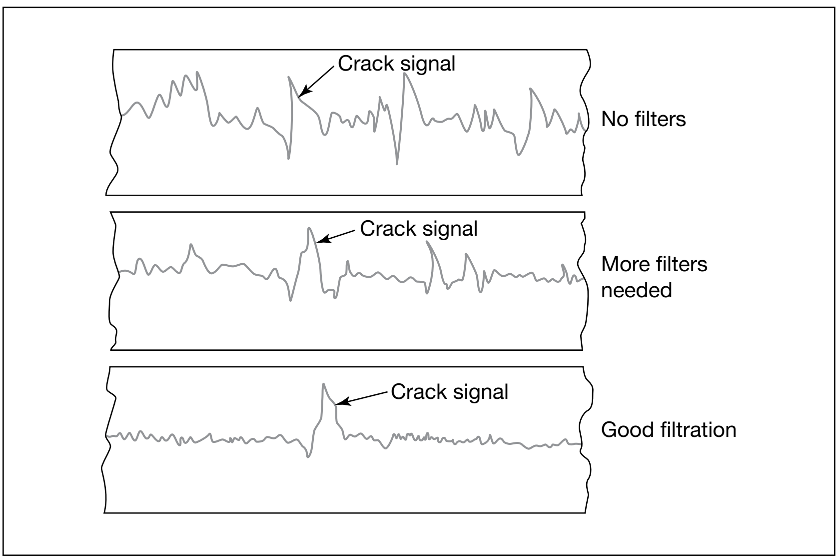


Figure 19. Suppression of noise.

10

Selection of Test Frequency

Test Frequency

The frequency of an alternating current is defined as the number of cycles (one complete cycle of current) that occur in 1 s. Its unit is the hertz, one hertz (1 Hz) being one cycle per second. Thus, house current at 60 cycles per second has a frequency of 60 Hz. The most important parameter of the test system that affects the depth of penetration is the test frequency.

The type of alloy involved and the variables to be measured or suppressed determine the best frequency. For a given alloy, higher frequencies normally limit the eddy current test to inspection of the excited metal surface nearest the primary coil winding. Lower frequencies permit deeper eddy current penetration. At any selected test frequency, eddy currents will penetrate deeper in lower conductivity alloys than in higher conductivity alloys.

High test frequencies are normally used for detecting small surface cracks or surface contamination and for gauging thin coatings. Medium frequencies are useful for conductivity measurements such as alloy sorting. Low test frequencies are usually required for testing thicker materials (for opposite side corrosion, for example), for thickness gauging, and for penetrating into ferromagnetic materials.

Penetration depth, however, is only part of the process for selection of optimum eddy current test frequencies. The geometric relationship between the impedance curves for the variable magnitudes (different conductivity points or liftoff points) along their respective impedance curves is important.

Depth of Penetration

Eddy currents are not uniformly distributed throughout a test object. They are most dense at the surface closest to the coil and become progressively less dense with increasing distance below the surface of the material. At some distance below the surface of a thick material there will be essentially no currents flowing. The depth of penetration is affected by the frequency, conductivity, and permeability of the material.

- The depth of penetration decreases as the frequency increases.
- The higher the conductivity, the less the penetration.
- The higher the permeability, the less the penetration.

When testing ferromagnetic materials, the permeability factor will have no effect on the depth of penetration if the test object is magnetized to saturation by a separate direct current coil. The standard depth of penetration is defined as the depth at which the current strength has dropped to 37% of the current density that exists at the surface. Figure 1 shows the distribution of eddy currents in a material.

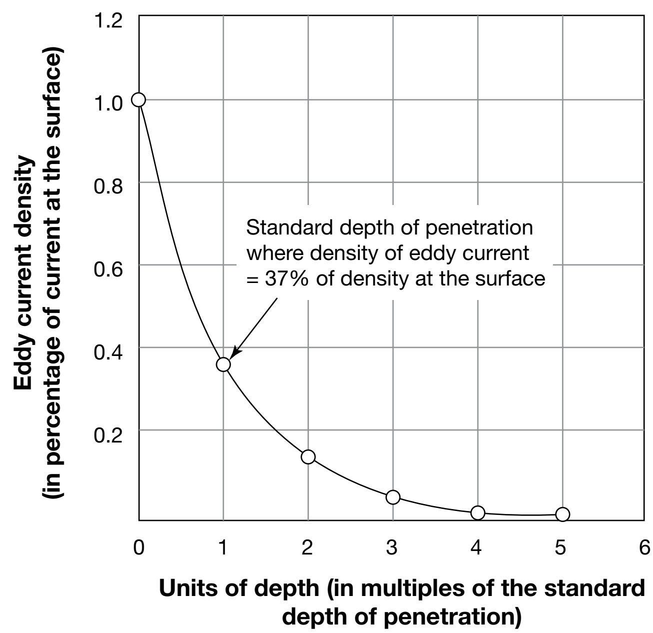


Figure 1. Variation in eddy current density.

If the standard depth of penetration exceeds the thickness of the material under test, the restriction of the eddy current paths appears as a change in the conductivity of the material. The coil response then reflects the thickness of the material. Eddy currents do not cease to exist beyond one standard depth. Normally, the material must have a thickness of two or three times the standard depth before thickness ceases to have any effect on the test coil. Figure 2 shows the standard depth of penetration for several materials with different conductivities at various operating frequencies.

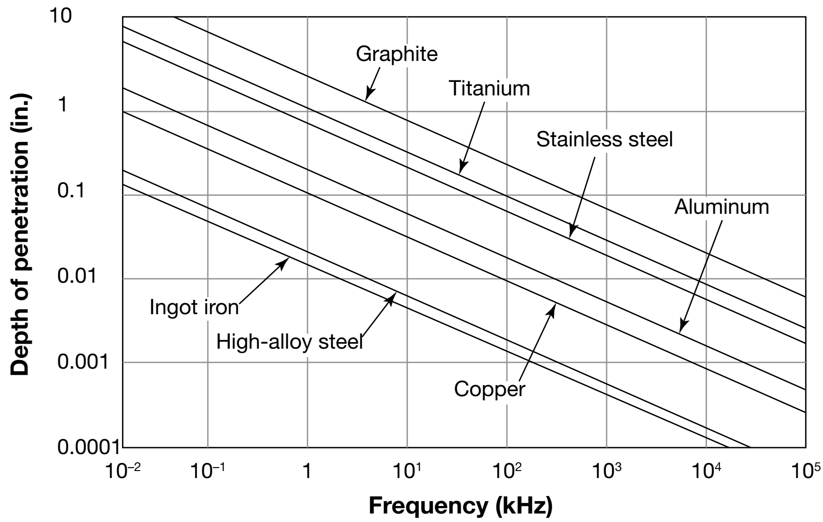


Figure 2. Standard depth of penetration versus frequency for different materials.

The standard depth of penetration (δ) is calculated as follows:

(Eq. 1)
$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

where
- δ is standard depth of penetration (m)
- π is 3.1416
- *f* is frequency (Hz)
- μ is magnetic permeability (H/m)
- σ is electrical conductivity (S/m)

Problem

A stainless steel block (300 series) is tested with a surface probe operating at a frequency of 100 kHz. Stainless steel (300 series) is nonferromagnetic. Its magnetic permeability (μ) is $4\pi \times 10^{-7}$ H/m. Its conductivity is 0.14×10^{7} siemens (mhos) per meter. What is the standard depth of penetration in millimeters for eddy currents in the block?

Solution

Given

$\pi = 3.1416$

frequency (f) = 100×10^3 Hz

magnetic permeability (μ) = $4\pi \times 10^{-7}$ H/m

conductivity (σ) = 0.14×10^7 S/m

Use the formula for calculating depth of penetration and plug in the numbers to calculate the answer as follows:

$$\delta = \frac{1}{\sqrt{3.1416 \times \left(100 \times 10^3\right) \times \left(4 \times 3.1416 \times 10^{-7}\right) \times \left(0.14 \times 10^7\right)}}$$

$$\delta = \frac{1}{\sqrt{3.1416 \times 100\ 000 \times \left(12.5664 \times 0.0000001\right) \times \left(0.14 \times 10\ 000\ 000\right)}}$$

$$\delta = \frac{1}{\sqrt{552\ 700.43}}$$

$$\delta = \frac{1}{743.438}$$

$$\delta = 0.00135 \text{ m}$$

$$\delta = 1.35 \text{ mm}$$

Thus, the depth of penetration for this particular situation is 1.35 mm (0.05 in.).

Limit Frequency

An equation for determining the limit frequency (f_g) is:

(Eq. 2) $$f_g = \frac{5066}{\mu_{rel} \sigma\, d^2}$$

where

f_g is limit frequency (Hz)

μ_{rel} is relative permeability

d is diameter of test object (cm)

σ is conductivity (m/Ω-mm^2)