MATERION

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TECHNICALTIDBITS

MATERION PERFORMANCE ALLOYS

Beauty is only skin deep, and so are high frequency electrical signals. – How high frequency electrical signals stay largely near the outer surface of conductors.

- **Impedance (Z)**
- **Inductive Reactance (X_L)**
- **Capacitive Reactance (X_C)**
- **Current Density**
- **Skin Effect**
- **Skin Depth (δ)**
- **Magnetic Permeability (μ)**

The next issue of Technical Tidbits will discuss discuss dielectric breakdown and related characteristics.

SKIN EFFECT AND SKIN DEPTH

Impedance is the relationship between voltage and current in a conducting circuit. It is made up of resistance, inductance, and capacitance. Together, inductance and capacitance create **reactance.**

Resistance (R) is determined by the electrical conductivity (inverse of the electrical resistivity) of the conductor. Inductance (L) is determined mostly by the geometry of the circuit (the amount of loop area that the circuit encloses). Capacitance (C) is determined by both geometry (distance between conductors) and material properties (dielectric constant and loss tangent of materials around the conducting element).

Inductive reactance (X_L) is defined as the driving frequency multiplied by the equivalent circuit inductance ($X_L=\omega L$). **Capacitive reactance (X_C)** is defined as the inverse of the driving frequency multiplied by the equivalent circuit capacitance ($X_C=1/\omega C$). Resistance, inductive reactance, and capacitive reactance all have units of ohms.

Recall that the overall impedance of a circuit or circuit element is defined as follows:

$$Z=\sqrt{[R^2+(X_L-X_C)^2]} = \sqrt{[R^2+(\omega L - {}^1/_{\omega C})^2]},\ \text{where } \omega=2\pi f$$

So, while resistance theoretically does not change with frequency (f), inductive and capacitive reactance do, and impedance depends greatly on whether the circuit is more inductive or more capacitive.

DC currents, by definition, have no change in voltage or current over time. Therefore, they do not experience reactance, and the path of least impedance is simply the path of least resistance. Under these conditions, current will flow uniformly throughout the cross section of a conductor, following the path of least resistance, minimizing energy loss due to resistive heating.

AC currents, on the other hand, must strike a balance between energy lost due to resistive heating and energy lost due to reactance. At high frequencies, the reactive loads (capacitive and inductive) tend to dominate impedance far more than the resistive loads. In fact, very high frequency AC currents may even follow the path of greatest resistance, if it means that the overall impedance is lower.

As a consequence of minimizing inductance, the current in a conductor moves to the outer surface, which reduces the internal magnetic fields in the conductor. The **current density** is maximum on the surface, dropping off exponentially toward the center of the conductor. This phenomenon is known as the **skin effect**. The **skin depth (δ)** is where the current density drops off to 1/e of its original value, so 74% of the current flows within 1 skin depth of the surface. Please note that while the skin depth and the loss tangent have the same symbol (δ), the two are unrelated.

Skin depth may be calculated as:

$$\delta = \sqrt{1/\sigma\pi\mu_0\mu_r f} = \sqrt{\rho/\pi\mu_0\mu_r f}$$

From this, you can see that skin depth depends only on the conductivity (or resistivity) of the metal, its **relative magnetic permeability**, and the frequency of the AC signal. Under DC conditions, the frequency goes to 0, and the skin depth goes to infinity, meaning that the current is uniform throughout the cross section of the conductor. Note that his applies to a single conductor. For a coaxial cable, where the return line surrounds the signal line, the skin effect pushes the current to the outside diameter of the inner conductor and the inside diameter of the outer conductor, which minimizes the current loop area.

At very high frequencies, such as at RF frequencies, the skin depth is less than the typical plating thickness, so most of the current flows in the plating. Surface roughness affects the impedance, as the signal follows the contours of the plating. The plating surface should be as smooth as possible, which also means that the base metal and any underplating layers should be smooth as well. Pay special attention to the surfaces where the current will be flowing, such as the inside diameter of the outer conductor in coaxial cables.

SKIN EFFECT AND SKIN DEPTH (CONTINUED)

Figure 1 shows the idealized skin depth in metal as a function of conductivity and magnetic permeability. The charts are linear, but for a lot of high permeability materials, the relative permeability is also a function of frequency, so real skin depth vs. frequency charts would be much more complex. The geometry of the conductor may also come into play as well.

One consequence of the skin effect is that the resistance of a conductor does become dependent on frequency. Resistance is calculated as follows: $R=\rho L/A$, where L is the length of the conductor and A is the cross-sectional area through which the current flows. If the skin effect pushes the current toward the outer surface, the overall cross-sectional area is effectively reduced, increasing the resistance. Since more current is being carried in the outer surface, more heat will be generated as well.

Skin depth is also important in electromagnetic shielding. As electromagnetic waves attempt to pass through metallic shielding, they generate currents in the metal, which take energy out of the wave. The skin effect ensures that most of the energy is removed within a few skin depths. For each skin depth, the signal strength is reduced by approximately 8.7 decibels. It takes only 11 skin depths to attenuate a traveling electromagnetic wave by a whopping 100 dB (99.99999999% reduction in strength). A nice consequence of the skin affect in electromagnetic shielding is that as the frequency of the signal increases, the shielding can be made thinner, so less metal is required.

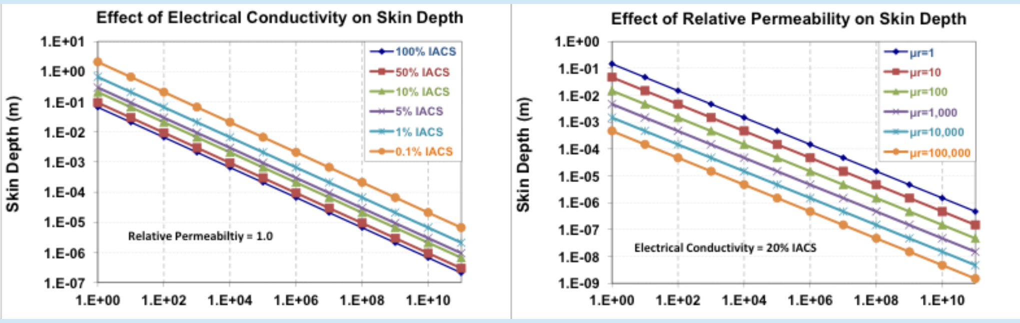

Figure 1 – Effects of Electrical Conductivity (Left) and Magnetic Permeability (Right) on Skin Depth.
In the conductivity graph, the relative permeability is held fixed at 1.0, which is a reasonable approximation for conductor metals like Cu, Au, Al, etc. In the relative permeability chart, a constant electrical conductivity of 20% IACS was chosen. Every metal or metallized substance will have a unique combination of conductivity and permeability.

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