1 Introduction

How a material interacts with radio frequency (RF) electromagnetic radiation greatly dictates its potential uses and applications. For some, the purpose of a device is to shield against specific RF frequencies. Other designers are trying to minimize electromagnetic interactions to help preserve signal clarity. In summary, Liquidmetal alloy is more transparent to RF signals than many materials of similar strength and hardness. Put another way, it is much more electromagnetically similar to titanium than to either copper or steel.

The ability of a material to shield or screen something from electromagnetic radiation is a function of:
1. Electrical resistivity ($\rho$)
2. Absolute magnetic permeability ($\mu = \mu_0 \times \mu_r$) where $\mu_0$ is the permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$ H/m) and $\mu_r$ is the relative permeability of the material.
3. Frequency of the radiation ($\omega = 2\pi \times f$)
4. Geometry of the shield
The practice of shielding is a matter of attenuating electromagnetic waves to the point where the signal is undetectable on the other side of the barrier. Any material with non-zero resistivity and non-zero permeability (everything except for classical superconductors) will attenuate an electromagnetic field to some extent. However, materials with low electrical resistivity (good conductors) and high magnetic permeability will produce the most effective shields. The opposite is true for materials with high resistivity. A common mathematical construct called skin depth \( \delta \) is often used to compare the shielding potential of metals, and refers to the AC current density distribution in the material. The skin depth can be approximated by

\[
\delta_s = \sqrt{\frac{2\rho}{\omega \mu}}
\]  

(1)

At the skin depth of the material, the electromagnetic field in the material has been reduced to \( (1/e \approx 36.8\%) \) of its magnitude at the surface ((or \( 1/e^2 \approx 13\%) \) of its incident power at the surface since the power of a wave is proportional to the square of a field quantity). The point here, is that we now have a convenient number by which to compare the stopping power of different metals at a specific frequency. Please note that this equation is an approximation of a more complete model when it is assumed that the material is a decent electrical conductor and that the incident frequency is much higher than \( (1/\rho \varepsilon) \) or similarly \( \sigma \gg \omega \varepsilon_0 \varepsilon_r \) where \( \sigma \) is the conductivity of the material and \( (\varepsilon_0 \) and \( \varepsilon_r \) are the permittivity of free space and the material respectively).

The definition for skin depth comes from the Beer-Lambert law, which describes the intensity of a plane electromagnetic wave inside a material as it is attenuated:

\[
I(x) = I_0 e^{-\frac{1}{\delta_s} x}
\]

(2)

where \( I(x) \) is the intensity at distance \( x \) into the material and \( I_0 \) is the original intensity of the incident wave.

We can also define an attenuation constant \( \alpha \) for a material which is the inverse of the skin depth

\[
\alpha = \frac{1}{\delta_s}
\]

(3)

and intuitive to use in the case of the RF shielding since a larger \( \alpha \) value of \( \alpha \) for a material indicates a higher degree of shielding for the same wall thickness and radiation frequency.
Another aspect to keep in mind is that electromagnetic radiation considered to be in the radio frequency range can be anywhere from about $3kHz$ to $300GHz$. This is a very wide range, so in practice it is best to understand the frequency of the RF application prior to establishing the thickness, design, or material decisions. The data in Table 1 on page 3 shows the common transmission/reception bands and their abbreviations within the generic designation of RF electromagnetic radiation.

Table 1: Table of radio frequency bands and their abbreviations. Knowing the frequency of electromagnetic radiation to be shielded against is an important part of any shield design project.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Wavelength</th>
<th>Designation</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-30 Hz</td>
<td>$10^5$ - $10^4$ km</td>
<td>Extremely low frequency</td>
<td>ELF</td>
</tr>
<tr>
<td>30 - 300 Hz</td>
<td>$10^4$ - $10^3$ km</td>
<td>Super low frequency</td>
<td>SLF</td>
</tr>
<tr>
<td>300 - 3000 Hz</td>
<td>$10^3$ - 100 km</td>
<td>Ultra low frequency</td>
<td>ULF</td>
</tr>
<tr>
<td>3 - 30 kHz</td>
<td>100 - 10 km</td>
<td>Very low frequency</td>
<td>VLF</td>
</tr>
<tr>
<td>30 - 300 kHz</td>
<td>10 - 1 km</td>
<td>Low frequency</td>
<td>LF</td>
</tr>
<tr>
<td>300 kHz - 3 MHz</td>
<td>1 km - 100 m</td>
<td>Medium frequency</td>
<td>MF</td>
</tr>
<tr>
<td>3 - 30 MHz</td>
<td>100 - 10 m</td>
<td>High frequency</td>
<td>HF</td>
</tr>
<tr>
<td>30 - 300 MHz</td>
<td>10 - 1 m</td>
<td>Very high frequency</td>
<td>VHF</td>
</tr>
<tr>
<td>300 MHz - 3GHz</td>
<td>1 m - 10 cm</td>
<td>Ultra high frequency</td>
<td>UHF</td>
</tr>
<tr>
<td>3 - 30 GHz</td>
<td>10 - 1 cm</td>
<td>Super high frequency</td>
<td>SHF</td>
</tr>
<tr>
<td>30 - 300 GHz</td>
<td>1 cm - 1 mm</td>
<td>Extremely high frequency</td>
<td>EHF</td>
</tr>
<tr>
<td>300 GHz - 3000 GHz</td>
<td>1 mm - 0.1 mm</td>
<td>Tremendously high frequency</td>
<td>THF</td>
</tr>
</tbody>
</table>
2 Example

Now that we have all the tools in place, let’s work out an example. Radio frequency identification (RFID) tags operate within a bandwidth from 300MHz to 3GHz. Let’s assume that we have an RFID tag system operating at 1.0GHz and that we want to keep a particular tag from being identified by a reader device by encasing it in a Liquidmetal sleeve. First, we need to know something about the sensitivity of the reader device. Let’s say that the reader is only powerful enough to detect the RFID tag when it is 10 cm from the reader, and that the tag can physically get as close as 1 cm from the reader. This means that our shield must make the tag ‘appear’ to be > 10 cm from the reader when it is actually 1 cm.

In free space, all electromagnetic waves obey the inverse-square law which states that the power density of an electromagnetic wave is proportional to the inverse of the square of the distance from a point source. To calculate the signal loss between the RFID tag and the reader at various distances, we use the free space path loss (FSPL) equation.

$$FSPL = \left(\frac{4\pi df}{c}\right)^2$$

Where $c$ is the speed of light and $d$ is the distance from the transmitter to the receiver. Which tells us that the signal at 1 cm is 14.2 times stronger than the signal at 10 cm. We can use equation 4 to determine that our shield will need to reduce the signal by about 7% of the original power in order for it to be effective. In other words, we need to solve for $x$ where $I(x) = 0.07 \times I_0$. 

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>LM105</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative magnetic permeability</td>
<td>$\mu/\mu_0$</td>
<td>0.99994</td>
<td>0.999991</td>
</tr>
<tr>
<td>Electrical resistivity</td>
<td>$\Omega \cdot m$</td>
<td>$1.60 \times 10^{-6}$</td>
<td>$1.68 \times 10^{-8}$</td>
</tr>
<tr>
<td>Skin depth</td>
<td>$\mu m$</td>
<td>20.13</td>
<td>2.063</td>
</tr>
</tbody>
</table>
Using the Beer-Lambert equation and the electromagnetic properties of Liquidmetal Alloy LM105 found in Table 2 on page 3, we find that the solution is \( I(0.756 \text{ mm}) = 0.07 \times I_0 \). Therefore, the minimum Liquidmetal wall thickness which will block the signal sufficiently in this application is 0.756 mm. If you use a traditional RF shielding material like copper in the same application (properties also shown in Table 2 on page 3), the result is merely 0.0775 mm.

**Figure 1: Calculated skin depth for Liquidmetal Alloy LM105 and copper using equation. (1)**

![Figure 1](image.png)

For reference, the figure above compares the skin depth for Liquidmetal alloy LM105 and copper over a range of frequencies from 1.0Hz to 10GHz.

The analysis provided above is a very rough approximation to the true physics taking place, but it does demonstrate the fundamental problem. We have not taken into account near-field effects, shield dimensions other than thickness, reflection losses, apertures, etc. Electromagnetic shielding theory is an extremely complex field of study and we encourage the reader to research the topic in more detail. A few resources are listed below to give a more complete understanding of these concepts.

In summary, a potential user can see that Liquidmetal alloy LM105 is not an efficient electromagnetic shielding material and is actually quite transparent to RF radiation when compared to ferrous materials with similar densities and strengths. However, with a large enough wall-thickness and Faraday cage designs, it is possible to create a barrier for weak signals if necessary.
3 Resources

1. Wikipedia “Skin Effect” article: https://en.wikipedia.org/wiki/Skin_effect

Wondering how Liquidmetal alloys might work for your application? We invite you to download our design guide and speak with Liquidmetal scientists and engineers. We are challenging everything you know about metal parts processing. Why not challenge us?

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