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Properties of Metals Used for RF Shielding

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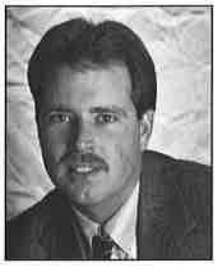

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Understanding the basic principles that influence a radio-frequency (RF) shielded enclosure's performance can be a tremendous help to someone tasked with specifying or purchasing a shielded enclosure. The choice of shielding materials and how they are assembled are crucial to the performance of the enclosure. Three factors are necessary for an RF shielded enclosure:

- The material chosen *must* provide the required level of shielding;
- Minimize the quantity of seams and penetrations in the enclosure to lower the potential points of deterioration; and,
- Maximize the quality of the seams and penetrations for better performance and long-term reliability.

Typically for low-frequency fields, the shielding effectiveness of an enclosure is largely determined by the material. At higher frequencies, seams and penetrations become the critical aspect of enclosure performance. The quality of seams and penetrations is affected by material and assembly technique.

Thin, highly-conductive metals which are pliable and resilient easily achieve RF integrity at seams and penetrations. The high conductivity requires less mechanical pressure to achieve a tight RF seal. Resiliency makes it possible to repeat the same RF seal at seams and penetrations in a modular system that is disassembled and reassembled. (Thin copper and certain screen meshes exhibit these properties.) an RF seal made with a resilient metal in a mechanically fastened design will almost always be better than seals made with a more rigid metal. Resilient metals will conform to each other and irregular surfaces better, making a tighter RF seal. These tighter seals also keep moisture out of the seam, which maintains its long-term RF integrity.

Aluminum, steel and galvanized steel are less conductive and more rigid (in typical thicknesses used) than copper. These more rigid metals can deform under the mechanical pressure required for a good RF seal. Once deformed, they retain their deformed shape, are hard to reform, and make it difficult to achieve repeatable shielding if the modular system is assembled more than once.

Frequencies typically shielded by RF enclosures can be anywhere from DC to 10 GHz, although shielding up to 40 GHz, and possibly 100 GHz, is sometimes required. A large selection of RF shielding materials is available. These range from paints and sprayed coatings to metallized fabrics and fibers to solid metals. This article will only consider solid metals because of their ability to attenuate RF signals to 100 dB or greater over a broad frequency range.

Shielding Background

The DC magnetic fields generated by magnetic resonance imaging (MRI) systems frequently need shielding. The magnet used in these systems is usually quite strong (.15 to 1.5 Tesla), and the magnetic field generated needs to be contained (to 5 gauss typically) within a well-defined space. This containment protects persons with pacemakers and certain types of implants, as well as electrical and electronic equipment in the immediate area.

Near fields exist within a distance of $\lambda/2\pi$ from the generating source, where λ is the wavelength. If the source is a monopole or dipole antenna, the major field generated within the $\lambda/2\pi$ distance is an electric field (E-field or high-impedance field). If the source is a loop antenna, the major field generated is a magnetic field (H-field or low-impedance field). In both cases, the strength of the predominant field decreases inversely proportional to the cube of the change in distance. This decrease in field strength is important when looking at the source-to-shield distance and the level of shielding required. Most test specifications have a source antenna located much closer to the shield (12 inches) than most fixed disturbing sources. Simply moving from one foot to two feet away (a change of 2× the distance), the strength of the predominant decreases to one eighth of its original strength ($1/2^3$). This is an important point to keep in mind when specifying an enclosure to shield against low-frequency magnetic fields.

Electric fields are easily attenuated by most metals. Attenuation of DC and low-frequency magnetic fields requires a metal that has ferrous properties or a high permeability μ. Permeability is the ratio of the magnetic field strength H to the magnetic flux density B within the material. In non-ferromagnetic materials, $\mu \approx 1$. For ferromagnetic materials, the permeability ranges from a few hundred to over 100,000. As the frequency increases in low-frequency magnetic fields, the need for permeability in the shield material begins to decrease. Above 10 MHz, the need for permeability basically disappears.

The distance $\lambda/2\pi$ from the generating source is known as the transition field, or the point at which near fields become far fields. (In practice, 1λ is considered the beginning of the far field condition.)

Far fields (plane waves) are characterized by their impedance in free space of 377 Ω. This impedance is independent of frequency. In the far field, both E- and H-field strengths decrease at a rate inversely proportional to the change in distance. Since power is proportional to E times H, the power of the

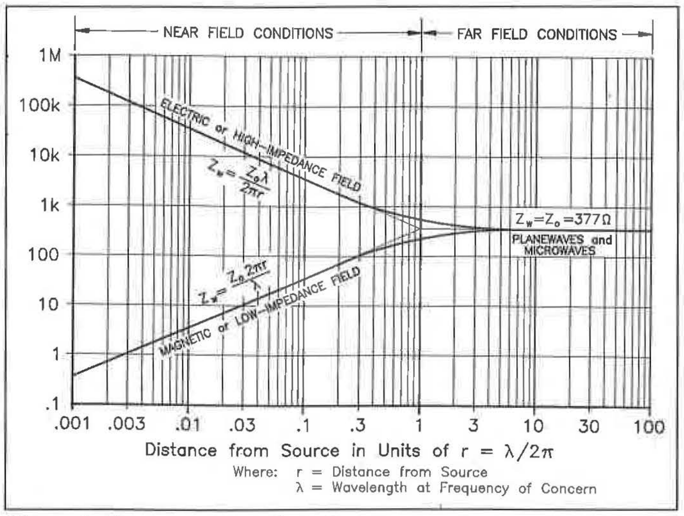


Figure 1. Free-space wave impedance..

planewave field is inversely proportional to the square of the change in distance. Figure 1 shows a graphical representation of the near field and far field conditions in relation to $\lambda/2\pi$ and impedance.

Planewaves are easily attenuated by any solid conducting metal and material thickness requirements decrease as frequency increases. In the upper MHz frequency range and beyond, shielding effectiveness becomes largely a function of seam and penetration integrity. The cutoff frequency fc of an opening is the frequency at which RF energy will propagate through the opening without being attenuated. Frequencies above fc will propagate freely, while those below fc are attenuated. However, frequencies just below fc may not be attenuated to the required level.

The length of the opening will also factor into the shielding effectiveness of a waveguide-beyond-cutoff feedthrough. (A general rule is to have 4X the diameter or 4X the widest dimension as the required length of the feedthrough.) The cutoff wavelength λ_c is :

- For circular feedthroughs: $\lambda_c = 3.412r$ where r = radius of the feedthrough
- rectangular feedthroughs: $\lambda_c = 2a$ where a = widest dimension of the feedthrough
- The cutoff frequency, f_c, is: $f_c = c/\lambda_c$, where c = speed of light.

The RF shielding effectiveness of a material is a function of the field type impinging on the surface, the frequency of the RF energy, and the material's conductivity and permeability. Shielding results from reflection of energy off the surface of the metal; absorption of energy as it passes through the metal; and re-reflection at the second surface. Figure 1 shows that electric fields experience a significant impedance mismatch at the air-metal transition at low frequencies. This mismatch results in a large amount of reflected energy. On the other hand, magnetic field impedances are very low so a significant amount of RF energy couples into the shield material, thereby reducing its shielding effectiveness.

The skin depth δ determines the absorption characteristics of the shielding material. The smaller the skin depth, the thinner the material can be for a required level of shielding. One skin depth is defined as the required thickness of a metal for an RF signal to be reduced to 37 percent of its original strength. Skin depth is calculated as follows:

$\delta = 1/(\pi f \mu \sigma)^{1/2}$
where: f = frequency
$\mu = \mu_o \mu_r$ and
$\mu_o = 4\pi \times 10^{-7}$ Henrys/meter
μ_r = relative permeability of the shielding material
σ = conductivity of the shielding material

This equation shows that whenever the frequency, permeability, or conductivity increases, the skin depth is reduced.

At high frequencies, frequency and conductivity are the major variables determining skin depth. However, at low frequencies a high permeability would reduce the skin depth and improve magnetic-field shielding characteristics.

Galvanic Corrosion and Oxidation

An area of concern for long-term reliability and performance of RF shields is galvanic corrosion. Galvanic corrosion can occur when two dissimilar metals (metals that have a potential difference due to conductivity differences) come in contact with each other. Gold, silver, and copper are cathodic and will not readily corrode when placed in contact with other metals. Metals such as zinc and magnesium are anodic and will readily corrode when placed in contact with other metals. Table 1 lists the galvanic series of metals. To eliminate or minimize galvanic corrosion, it is always best to join dissimilar metals that are as close to each other in the galvanic series as possible. It is also important to avoid contact areas of small anodes and large cathodes; avoid dissimilar metal contacts in corrosive environments; and use an intermediate layer of a third metal that is neutral or near neutral to each of the dissimilar metals

Corroded End (Anodic, or least noble)
Magnesium Magnesium allloys
Zinc
Aluminum 1100
Cadmium
Aluminum 2017
Steel or Iron Cast Iron
Chromium iron (active)
Ni-Resist Irons
18-8 Chromium-nickel-iron (active - 304 S.S. 18-8-3 Cr-Ni-Mo-Fe (active) - 316 S.S.
Lead-tin solders Lead Tin
Nickel (active) Inconel (active) Hastelloy C (active)
Brasses Copper Bronzes Copper-nickel allloys Monel
Silver solder
Nickel (passive) Inconel (passive)
Chreomium-iron (passive) Titanium 18-8 Chromium-nickel-iron (passive) 18-8-3 Cr-Ni-Mo-Fe (passive) Hastelloy C (passive)
Silver
Graphite Gold Platinum
Protected End (cathodic, or more noble)

Table 1. Galvanic Series of Metals.

being separated.

Oxidation of the metals being used must also be considered. All metals typically used for shielding will oxidize to some extent since they are in constant contact with the atmosphere. Copper oxide is semi-conductive, while aluminum oxide is a dielectric and could destroy the integrity of an RF shield if it is not removed before assembly. In general, all mating surfaces of RF shield components should be cleaned prior to assembly, regardless of which material is used.

Figure 2 shows the conductivity/ resistivity of four metals commonly used in RF shielding.

Copper

Copper (and its alloy, brass) is one of the most versatile and widely used RF shielding materials. It can be formed, fabricated, and soldered easily. It is highly conductive (5.80 x 10^7 Ω/m) and does not oxidize rapidly when exposed to normal atmospheric conditions.

The ease of forming and fabricating is important for manufacturing and field modification. Manufacturing times can be decreased because simpler fabrication techniques can be used. More creative shield configurations can also be implemented. Copper is typically used in 3-oz. (.0042"), 12-oz. (.0168"), and 24-oz. (.0336") stock thickness. 3-oz. copper can be used in most shielding applications. 12-oz. and 24-oz. copper are used in applications where higher performance or more strength and durability is required. For example, at 1 kHz the skin depth of copper is .0823". While the thicker copper sheet is not ideal, it offers far superior shielding over the thinner 3-oz. copper.

Slow oxidation is another benefit of copper. Any oxide layer that does form is easily removed prior to assembly. Galvanic corrosion is minimized since copper is cathodic with respect to other metals. However, putting other metals in contact with copper (for penetrations, feedthroughs, etc.) must be done with care to avoid galvanic corrosion of the second metal. The mating surface of the second metal must be properly treated, or galvanic corrosion could eventually compromise the shielding integrity of the enclosure.

Drawbacks to copper are the fact that it is non-ferrous and expensive. Ferrous properties (high μ) are required for good low-frequency and DC magnetic field shielding. Heavy gauge copper offers good shielding down into the kHz region, but the performance versus cost makes copper unattractive for low-frequency magnetic-field shielding.

Aluminum

Aluminum is a second commonly-used RF shielding material. As a wall covering, the aluminum sheet typically used is a heavier gauge than its copper counterpart and so can be more difficult to fabricate and form. Field modifications and repairs are also more difficult. Despite these drawbacks, aluminum is still a very useful material for fabricating components used in RF shielded enclosures. Aluminum's non-ferrous properties and strength-to-weight ratio, coupled with the ability to extrude custom shapes and design larger components for reduced weight, make it particularly appealing for certain applications.

Using aluminum for RF shielding requires particular attention to its oxidation characteristics and its galvanic corrosion potential. Aluminum will form an oxide layer within hours after being exposed to the atmosphere. This oxide will stop forming after it reaches a certain thickness and it will help prevent further oxidation. However, aluminum oxide dissolves in the presence of strong alkaline chemicals and solutions, and rapid attack of the aluminum follows. For this reason, aluminum should never be placed in direct contact with lime-bearing cements or concrete (lime being a very strong alkaline chemical). Aluminum oxide is a ceramic, which is great for protecting the aluminum, but terrible for making an RF seal. An abrasive can be used to remove the oxide layer just before the RF seal is made. (The RF seal can also be effectively made by having contact areas that create a wiping action on the aluminum by the second mating surface. This wiping action would be used in areas where seals are not permanent, such as at doors and hatches.) Then the aluminum surface would be coated to prevent oxidation from forming again and to make the surface galvanically compatible with the second mating surface. The coatings can be in the form of a plating, an arc or flame-sprayed metallized layer, or a conductive tape. However, not all coatings hold up well in abrasive conditions.

Being non-ferrous, aluminum also exhibits reduced low-frequency magnetic-field shielding. Since aluminum has only 50 to 60 percent of the conductivity of copper, a thicker gauge of aluminum would be required to achieve the same shielding effectiveness as copper.

Steel

Steel, in its various forms (galvanized, annealed, unannealed, hot-rolled, cold-rolled, etc.), is the third metal commonly used for RF shielding. Steel, and other ferromagnetic materials, provides the low-frequency magnetic-field shielding characteristics that are missing with copper and aluminum. Steel is manufactured in many different forms and alloys that influence its permeability greatly, and because of this it can be more difficult to specify for low-frequency magnetic-field shielding. Steel alloys exhibit a wide range of properties depending on whether they are low-carbon or high-carbon, annealed or unannealed, hot-rolled or cold-rolled, and whether they are grain-oriented or not.

Low-carbon steel is typically specified for DC and low-frequency magnetic shielding because it has a higher permeability and saturation point than high-carbon steel. Saturation is the maximum magnetic flux density the material is capable of containing within a particular thickness.

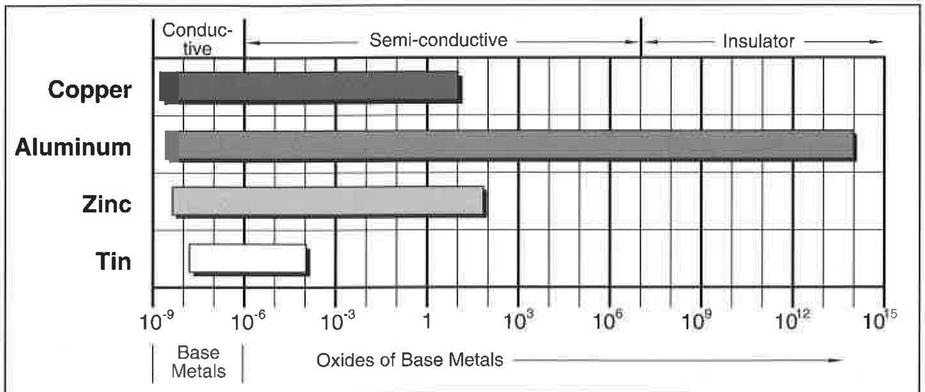
The grain orientation of steel plates is determined at the fabrication plants. Grain orientation has a significant influence on magnetic field performance in plates that are at least 1/4" thick. The grain of the steel should be oriented in the direction of the magnetic flux being generated. Magnetic flux is analogous to electrical current in that it will always follow the path of least resistance. Having the grain of the steel oriented with the direction of the magnetic flux will offer the least resistance to the magnetic flux.

Annealing enlarges the grain structure of the steel. This relieves internal stresses and enhances the magnetic properties of the steel. Annealing will cause a loose, flaky carbon scale to form on the surface of the steel plates or sheets. This scale should be removed before assembly for better welds and a cleaner installed product.

Cold-rolled steel (CRS) has better shielding characteristics than hot-rolled steel (HRS), but HRS has better mechanical properties. Both are easily welded. The surface finish difference between CRS and HRS will most likely affect the metal choice. HRS has a dry, semi-oxidized and scaly surface; while CRS has a smooth, clean, and oily surface. The end use and final exterior/interior finish would most likely be the deciding factor as to which type of steel sheet to use. Annealed CRS and HRS will both exhibit a scale on the surface, so this should be kept in mind if the steel will be exposed.

The steel or steel alloy used, its thickness, annealing (if any), and grain orientation, are all important to insure that the steel does not reach its saturation point before the desired level of magnetic field shielding is achieved.

Steel used for RF shielding is typically protected from the environment for the duration of its use. Iron oxide (rust) will form to some extent and must be removed on mating surfaces and shield



Material	Base Metal Resistivity	Oxide Resistivity
Copper	1.72×10^{-8}	10 (max)
Aluminum	2.62×10^{-8}	1×10^{14}
Zinc	6×10^{-8}	94.4
Tin	11.4×10^{-8}	4×10^{-4}

Figure 2. Resistivities of metals and their oxides in Ω-m.

penetrations. RF integrity and electrical continuity will be jeopardized by oxidation. A continuous weld between two sheets of steel will perform better than a mechanical seam. For high performance at extremely high frequencies (up to 100 GHz), welded steel enclosures are generally the most practical choice. However, welders that work on these rooms must be trained and certified in their craft. Due to the cost and special handling requirements, smaller steel enclosures may be cost prohibitive if low-frequency or DC magnetic field shielding and/or extremely high-frequency shielding is not required. Modular panel designs using copper, aluminum, or galvanized steel sheets can typically meet or exceed 100 dB at 10 GHz. Modular designs are also less expensive, lighter and easier to transport to the construction location inside a building.

Galvanized steel sheets are often used in modular panel designs to minimize corrosion and oxidation. The zinc galvanizing protects the steel from oxidizing, yet the zinc itself can experience galvanic corrosion if proper precautions are not followed. Also note that the zinc does not provide corrosion protection at the cut edges of the steel sheets. And, unlike copper, tin and aluminum oxide, iron oxide (rust) does not stop forming after it reaches a certain thickness. Zinc is one of the most anodic (most prone to corrosion) of all metals typically used in RF shielding. Direct contact with copper should definitely be avoided. Galvanized steel offers better low-frequency and DC magnetic-field shielding than copper or aluminum, but can have problems at higher frequencies. If mechanical seams are used, greater clamping pressure will almost always be required to obtain the same level of performance that would be realized with a copper shield at lower clamping pressures. And with a rigid material such as steel, it is harder to get repeatable RF seals in a modular enclosure if it is disassembled, moved, and then reassembled. Seam performance of the typical modular enclosure is most vulnerable at the floor, also the area where moisture is likely to be most prevalent. For this reason, floor seams should be minimized or eliminated altogether. If galvanized panels are welded, great care must be taken to insure the safety of the welders from the toxic fumes emitted from zinc.

Copper:	Semi-conductive oxide layer adheres to the surface and prevents corrosion from penetrating. Sensitive to elevated concentrations of sulfate, chloride or ammonia compounds, and sulfide. Not corroded by non-oxidizing salt solution. Is safe to use in contact with lime-bearing cement or concrete.
Aluminum:	Insulating (ceramic) oxide layer forms rapidly in air, adhering firmly to the surface of the aluminum, and halts futher corrosion. Sensitive to alkaline compounds and halogen acids. Resists acetic and organic acids. Contact with portland cement, lime, and plaster should be avoided.
Zinc:	Air causes basic carbonate to form. This acts as a protective layer and prevents further corrosion. Sensitive to alkaline materials and sulphurous components in the air. Should not be placed in contact with cement or lime-mortar.

Table 2. Corrosion and oxidation properties of metals.

Interface Materials

When dissimilar metals must contact each other, a number of surface treatments can be applied to one or both surfaces to make them compatible. These surface treatments can be plating, conductive adhesive foil tapes, or flame or arc sprayed metal compound. In all cases, the base metal being treated must be cleaned of all oxides, corrosion, dirt, or other contaminants to insure good adhesion. To minimize oxidation, it is important to treat the surface of the base metal most affected by oxidation. For example, it would be better to treat the surface of newly cleaned aluminum or steel to prevent oxidation. Treating newly-cleaned copper would still allow oxidation to form on the aluminum or steel, even though the two base metals would be galvanically compatible.

Plating is a good technique for applying an interface material, and tin plating is generally the best choice. Tin can be applied over most metals used for RF shielding and provides a surface that is easily soldered, making certain fabrication processes easier. However, plating can be cost prohibitive if the shape is too complex, or too large.

An arc-sprayed or flame-sprayed surface treatment offers a good alternative for applying an interface material. In this process, molten metal is deposited directly on a clean base metal surface and forms a permanent bond. Many metals and metal alloys can be arc- or flame-sprayed.

Another surface treatment is copper or tinned-copper foil tape with a conductive pressure sensitive adhesive. Conductive tape works best below 1 GHz. Above 1 GHz, the random displacement of the conductive particles in the adhesive becomes apparent.

Strips of metal, usually a tinned-copper material, can be used as interface surface treatments. The strips would be clamped between the two components being assembled, and this works best when at least one surface has some resiliency. Unlike plating, arc or flame spraying, or taping, the strips of metal will not prevent oxide from forming on the base metals.

Conductive paints, silicones, epoxies,

and other flowable coatings are not recommended for metal-to-metal interface contacts because of the random displacement of conductive particles within the dielectric medium.

The most common interface metal used is tin. Tin is compatible with most other metals used for RF shielding: copper, aluminum, galvanized steel, and steel. Tin oxidizes slowly and the oxide layer that forms is very thin, brittle, and easy to break through. The oxide layer is also more conductive than copper oxide, though the best practice is to remove any oxide before assembling components. Tin also provides an excellent surface for soldering. Tin is soft and pliable, which allows it to adhere to flexible surfaces without flaking or peeling. A number of studies show tin to be a highly desirable material for its ability to maintain high conductivity (and shielding effectiveness) over long periods in corrosive environments.

Zinc is another interface metal used as a protective coating on steel. The galvanic series chart in Table 1 shows that tin and aluminum are the only shielding metals used that are compatible with zinc.

Chromate coatings for aluminum work well as oxide inhibitors, keeping the aluminum surface conductive. But these coatings are typically only a few millionths of an inch thick and do not bond well with aluminum; thumbnail pressure can remove the coating in most cases. The coating is a salt form of chromate, not a metallic form, and because of this will not protect against galvanic corrosion.

Summary

Copper, aluminum, steel, and galvanized steel all have their merits and their drawbacks. Table 2 lists some of the corrosion and oxidation characteristics of copper, aluminum, and galvanized steel (zinc).

The metal used to construct an RF shield should be chosen based on shielding needs. Then steps must be taken to minimize seams and penetrations and prevent the formation of oxidation and galvanic corrosion, This will insure a high level of shielding effectiveness and long-lasting performance.

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