Microengineered Multilayer Films for Shielding Applications

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INTRODUCTION

Shielding low frequency magnetic waves continues to be essential both to prevent emissions and to shield sensitive equipment. Shielding these fields at low frequencies is difficult and usually requires thick layers of high permeability material. Plane waves, especially at low frequencies, can be shielded with highly conductive metals (copper) to produce a large reflection at the surface, with this reflection being essentially independent of the thickness. For H-fields (magnetic waves), the attenuation after the wave has entered the metal is the dominant shielding mechanism. For this low frequency shielding, thick magnetic metals in shapes such as welded steel panels are typically used, increasing the weight, cost, and complexity of retrofitting an existing room.

This article discusses the use of a layered structure consisting of alternating layers of a good conductor and a magnetic material. An improvement in properties occurs when the absorption in each layer is low. In this case, there is an effective averaging of the values of the conductivity and the permeability, resulting in a composite material with higher absorption than either material treated separately. This averaging model has been verified by detailed calculations of transmission through multilayer films and by measurements of an electrodeposited layered structure.[1]

Shielding low-frequency magnetic waves does not always require thick layers of high permeability material.

SHIELDING

The shielding effectiveness of a material is due to the reflection which occurs at the interfaces and the absorption of the fields after it enters the material (neglecting re-reflection losses). The reflection loss, R, of a plane wave from the front surface can be calculated from Reference 2 as

$$R_{dB} = 108 + 10\log_{10}[\sigma_{cu}/\mu_r f_{MHz}]dB$$

where σ_{cu} is the conductivity relative to copper, μ_r is the relative permeability and f_{MHz} is the frequency. The reflection is highest for highly conductive films with low permeability. The reflection loss for near field or magnetic waves is more complicated and can be zero under certain combinations of distance, conductivity and permeability.

The absorption loss, A_{dB}, occurs after the wave penetrates the film and can be expressed as

$$A_{dB} = 3.4\,t\,(f_{MHz}\sigma_{cu}\mu)^{.5}$$

where t is the thickness in mils. In this case, the higher the conductivity and permeability, the higher the absorption. Nickel alloys with proper anneals can have very high permeability. Their conductivity is much lower than copper, which reduces both the reflection and absorption, but this is offset by the increased absorption from the significantly higher permeability (10^4 or more).

A composite structure with high shielding for both magnetic fields and electric fields can be achieved by combining a highly conductive outer layer, which gives very high plane wave shielding at low frequencies, with a highly magnetic inner layer to improve the overall shielding. Such structures have been proposed[3] and the increase in shielding which occurs when multiple layers are used has been observed.[4,5] However, what is not obvious is that when multiple layers are used with individual layer thicknesses especially selected to keep the attenuation in each layer small, the interaction between the two materials results in an increase in the absorption compared to a simple summing of the absorption in each layer. By averaging the electrical properties, an essentially new material results.

Averaging the electrical parameters of the composite structure is widely used in optics to predict the refractive indices of mixed component systems.[6] Generally, the effective media theory modifies ε and μ by a shape factor and the volume percent. For a good conductor, with the imaginary part of the dielectric constant much greater than the real part, the conductivity can be averaged. With very thin laminar films, this reduces to a simple thickness average of the susceptibility and the conductivity (Figure 1). For high μ materials, this can be approximated by

$$\mu_{ave} \sim \frac{\mu_1 t_1 + \mu_2 t_2}{t_1 + t_2}$$

where $\mu_{1,2}$ and $t_{1,2}$ refer to the permeability and thickness of the respective layers.

Similarly, the average conductivity is given by

$$\sigma_{ave} \sim \frac{\sigma_1 t_1 + \sigma_2 t_2}{t_1 + t_2}$$

As an example of the improvements possible with this approach, Table 1 lists the

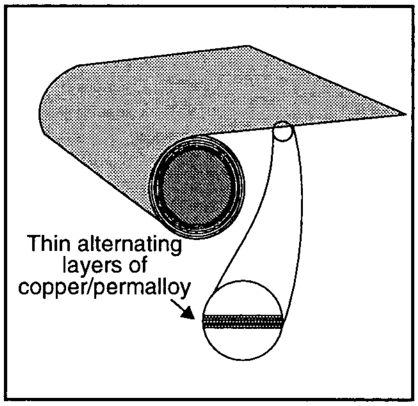

Figure 1. *Composite Structure.*

conductivity and permeability of copper, a highly magnetic film (permalloy), and measured values on an electroplated film. The film consists of equal layers of copper and permalloy where μ_r for electrodeposited permalloy is much lower. For a material such as permalloy, typical values are σ_{cu} = 0.027 while μ_r = 20,000.

Since half of the film thickness consists of copper, this improvement comes with a reduction in material cost. In the case of permalloy, the high permeability requires a high magnetic anneal, and with subsequent flexing or bending the μ_r is lowered significantly. The electrodeposited film has lower permeability with an absorption value per thickness of approximately 2/3 of the high μ permalloy, but at a lower cost, with easier handling and a higher plane wave reflection coefficient.

AVERAGING

This simple model was verified by calculations of transmission through multilayer films. The computer programs which were used addressed the effects of interaction between layers. These results are shown in Figure 2, which plots the transmission (in dB at a frequency of 10 MHz) versus the total film thickness for a film consisting of alternating layers of a high μ and a high σ film, along with a film consisting of layers of magnetic film only. The rapid changes in transmission near the surface are a result of the strong increase in reflection as the film becomes electrically thick. This rapidly saturates, and as expected, the single component magnetic film reaches a constant slope which agrees with the calculated skin depth. However, the films with different layers show a different behavior. At thinner layers, there is a higher slope (more absorption) which approaches that of the single component film at thicker layers, where the interaction is reduced. This calculated shielding is actually better than predicted from the simple effective media concept, but is not fully understood.[6] The same structure modeled with a program which treats each layer separately, but does include reflection at each interface, results in a constant slope with the total absorption equal simply to the

	COPPER	PERMALLOY	MIXED	ELECTRODEPOSITED
σ_{cu}	1	0.027	0.5	0.5
μ_r	1	20,000	10,000	500
$\sigma_{cu}\mu_r$	1	540	5,000	250 (measured)
Reflection (dB) (plane wave @ 1 kHz)	138 dB	80	95	95
Absorption (10 mils @ 1 kHz)	1.0	24.5	74.6	16.5

Table 1. *Conductivity and Permeability.*

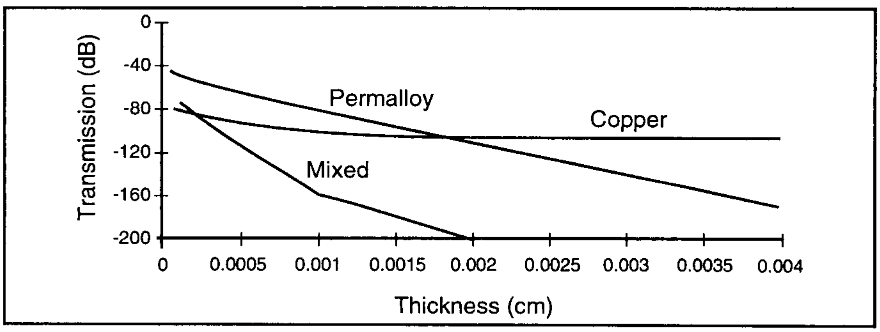

Figure 2. *Calculated Transmission in 3 Films Consisting of 20 Layers. Permalloy curve has 20 layers of permalloy. Copper curve has 20 layers of copper. Mixed curve has alternating layers of copper and permalloy.*

sum of the absorption in each layer. This is equivalent to having the thickness of each layer large compared to the penetration depth, which limits the thickness of individual layers to a few microns even at frequencies as low as 10 kHz. This requires the fabrication process to be capable of producing films of this thickness while maintaining good properties.

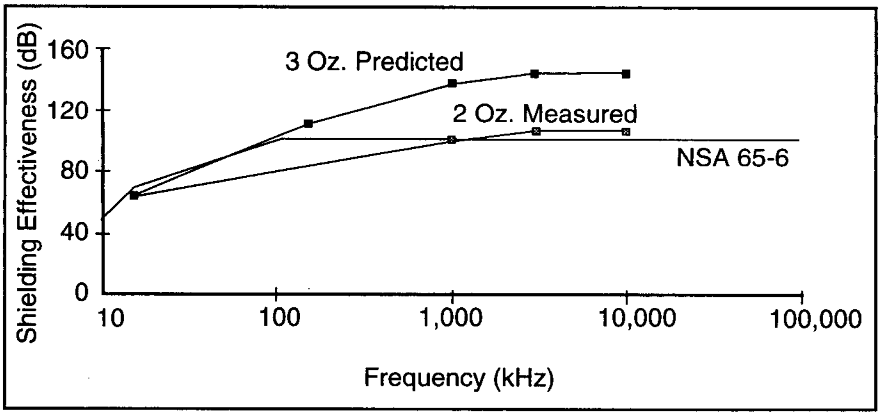

Figure 3. *Measured Shielding Effectiveness of Layered Films.*

MEASUREMENTS

Electrodeposition gives considerable flexibility in both the type of deposited material and their thicknesses. It allows the structure to be microengineered with the properties optimized to maximize the shielding. For example, the surface can be graded to 100% copper or even silver for high reflectivity for plane waves, while the bulk of the film will grade toward the optimum for absorption, nominally 50%. The exterior surfaces can be plated with metals optimized for corrosion resistance for electrical contact. The skin depth is not highly sensitive to the composition and a film with thicker copper degrades the performance slightly, but since nickel is considerably more expensive than copper, it can reduce the material cost.

Films consisting of alternating layers of 0.15-mil copper and permalloy (80% nickel, 20% iron) were deposited onto a starting substrate of 0.7 mil copper foil. These films were deposited without a bias field, so the permeabilities were typically around 1000. The size of the initial films was limited, and low frequency magnetic field measurements are difficult due to leakage at the edges. Samples of various thicknesses were measured using aperture test techniques to determine shielding effectiveness (Figure 3). Extrapolation of these measurements indicates that composite films of 3 oz./ft.[2] (nominally 0.004" thick) can meet NSA 65-6 requirements. Thicker films can be electrodeposited and improvements in the permeability of the permalloy will extend this performance to lower frequencies.

In addition to saving weight and thickness, the material has two additional advantages: easier seam connections and decreased sensitivity to any bias fields. A major problem with H-field shielding is maintaining the shielding effectiveness at the seams or joints. Good shielding effectiveness requires that either the magnetic contact be maintained across the seam (e.g., by welding), or that the seams be overlapped with very small gaps. Fabricated as thin conformal sheets with a copper outer layer, an overlapped seam and a solder joint can provide a low-impedance joint even for low-frequency magnetic fields.[7] This approach requires overlaps of a few inches and solder thickness well below 0.001", but this is possible due to the flexibility of the sheet.

Electrodeposition gives considerable flexibility in both the type of deposited material and their thicknesses.

CONCLUSION

The effectiveness of a new microengineered shielding system, including methods of interconnections, and a corresponding decrease in cost and weight has been demonstrated. The microstructural engineered thin-film shielding system is more flexible than existing approaches and offers higher performance, lighter weight, easier installation, and improved cost-effectiveness. The major applications will be at low frequencies such as electromagnetic pulse, TEMPEST, and high-power microwave applications. Requirements for the electromagnetic shielding of composite structures can also be met with this material, and the electroless deposition process makes this approach attractive for applying the layers directly to complex composite structures.

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