Materials for Electromagnetic Interference Shielding

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Materials for the electromagnetic interference (EMI) shielding of electronics and radiation sources are reviewed, with emphasis on composite materials and resilient EMI gasket materials, which shield mainly by reflection of the radiation at a high frequency.

1. Introduction

Electromagnetic interference (EMI) shielding refers to the reflection and/or adsorption of electromagnetic radiation by a material, which thereby acts as a shield against the penetration of the radiation through the shield. As electromagnetic radiation, particularly that at high frequencies (*e.g.*, radio waves, such as those emanating from cellular phones), tends to interfere with electronics (*e.g.*, computers), EMI shielding of both electronics and the radiation source is needed and is increasingly required by governments around the world. The importance of EMI shielding relates to the high demand of today's society on the reliability of electronics and the rapid growth of radio frequency radiation sources.[1–9]

The EMI shielding is to be distinguished from magnetic shielding, which refers to the shielding of magnetic fields at low frequencies (*e.g.*, 60 Hz). Materials for EMI shielding are different from those for magnetic fielding.

2. Mechanisms of shielding

The primary mechanism of EMI shielding is usually reflection. For reflection of the radiation by the shield, the shield must have mobile charge carriers (electrons or holes), which interact with the electromagnetic fields in the radiation. As a result, the shield tends to be electrically conducting, although a high conductivity is not required. For example, a volume resistivity of the order of 1 Ω·cm is typically sufficient. However, electrical conductivity is not the scientific criterion for shielding, as conduction requires connectivity in the conduction path (percolation in case of a composite material containing a conductive filler), whereas shielding does not. Although shielding does not require connectivity, it is enhanced by connectivity. Metals are by far the most common materials for EMI shielding. They function mainly by reflection due to the free electrons in them. Metal sheets are bulky, so metal coatings made by electroplating, electroless plating, or vacuum deposition are commonly used for shielding.[10–25] The coating may be on bulk materials, fibers,

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or particles. Coatings tend to suffer from their poor wear or scratch resistance.

A secondary mechanism of EMI shielding is usually absorption. For significant absorption of the radiation by the shield, the shield should have electric and/or magnetic dipoles, which interact with the electromagnetic fields in the radiation. The electric dipoles may be provided by $BaTiO_3$ or other materials having a high value of the dielectric constant. The magnetic dipoles may be provided by Fe_3O_4 or other materials having a high value of the magnetic permeability,[10] which may be enhanced by reducing the number of magnetic domain walls through the use of a multilayer of magnetic films.[26,27]

The absorption loss is a function of the product $\sigma_r\mu_r$, whereas the reflection loss is a function of the ratio σ_r/μ_r, where σ_r is the electrical conductivity relative to copper and μ_r is the relative magnetic permeability. Table 1 shows these factors for various materials. Silver, copper, gold, and aluminum are excellent for reflection, due to their high conductivity. Superpermalloy and mumetal are excellent for absorption, due to their high magnetic permeability. The reflection loss decreases with increasing frequency, whereas the absorption loss increases with increasing frequency.

Other than reflection and absorption, a mechanism of shielding is multiple reflections, which refer to the reflections at various surfaces or interfaces in the shield. This mechanism requires the presence of a large surface area or interface area in the shield. An example of a shield with a large surface area is a porous or foam material. An example of a shield with a large interface area is a composite material containing a filler, which has a large surface area. The loss due to multiple reflections can be neglected

Table 1 Electrical conductivity relative to copper (σ_r) and relative magnetic permeability (μ_r) of selected materials[119]

Material	σ_r	μ_r	$\sigma_r\mu_r$	σ_r/μ_r
Silver	1.05	1	1.05	1.05
Copper	1	1	1	1
Gold	0.7	1	0.7	0.7
Aluminum	0.61	1	0.61	0.61
Brass	0.26	1	0.26	0.26
Bronze	0.18	1	0.18	0.18
Tin	0.15	1	0.15	0.15
Lead	0.08	1	0.08	0.08
Nickel	0.2	100	20	2×10^{-3}
Stainless steel (430)	0.02	500	10	4×10^{-5}
Mumetal (at 1 kHz)	0.03	20,000	600	1.5×10^{-6}
Superpermalloy (at 1 kHz)	0.03	100,000	3,000	3×10^{-7}

when the distance between the reflecting surfaces or interfaces is large compared to the skin depth.

The losses, whether due to reflection, absorption, or multiple reflections, are commonly expressed in dB. The sum of all the losses is the shielding effectiveness (in dB). The absorption loss is proportional to the thickness of the shield.

Electromagnetic radiation at high frequencies penetrates only the near surface region of an electrical conductor. This is known as the skin effect. The electric field of a plane wave penetrating a conductor drops exponentially with increasing depth into the conductor. The depth at which the field drops to $1/e$ of the incident value is called the skin depth (δ), which is given by

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

where

f = frequency,
μ = magnetic permeability = $\mu_0 \mu_r$,
μ_r = relative magnetic permeability,
$\mu_0 = 4\pi \times 10^{-7}$ H/m, and
σ = electrical conductivity in $\Omega^{-1}\text{m}^{-1}$.

Hence, the skin depth decreases with increasing frequency and with increasing conductivity or permeability. For copper, $\mu_r = 1$ and $\sigma = 5.8 \times 10^7 \ \Omega^{-1}\text{m}^{-1}$, so δ is 2.09 μm at a frequency of 1 GHz. For nickel, $\mu_r = 100$ and $\sigma = 1.15 \times 10^7 \ \Omega^{-1}\text{m}^{-1}$, so δ is 0.47 μm at 1 GHz. The small value of δ for nickel compared to copper is mainly due to the ferromagnetic nature of nickel.

3. Composite materials for shielding

Due to the skin effect, a composite material having a conductive filler with a small unit size of the filler is more effective than one having a conductive filler with a large unit size of the filler. For effective use of the entire cross section of a filler unit for shielding, the unit size of the filler should be comparable to or less than the skin depth. Therefore, a filler of unit size 1 μm or less is typically preferred, though such a small unit size is not commonly available for most fillers and the dispersion of the filler is more difficult when the filler unit size decreases. Metal coated polymer fibers or particles are used as fillers for shielding, but they suffer from the fact that the polymer interior of each fiber or particle does not contribute to shielding.

Polymer-matrix composites containing conductive fillers are attractive for shielding[28–59] due to their processability (e.g., moldability), which helps to reduce or eliminate the seams in the housing that is the shield. The seams are commonly encountered in the case of metal sheets as the shield and they tend to cause leakage of the radiation and diminish the effectiveness of the shield. In addition, polymer-matrix composites are attractive in their low density. The polymer matrix is commonly electrically insulating and does not contribute to shielding, though the polymer matrix can affect the connectivity of the conductive filler and connectivity enhances the shielding effectiveness. In addition, the polymer matrix affects the processability.

Electrically conducting polymers[60–79] are becoming increasingly available, but they are not common and tend to be poor

in the processability and mechanical properties. Nevertheless, electrically conducting polymers do not require a conductive filler in order to provide shielding, so that they may be used with or without a filler. In the presence of a conductive filler, an electrically conducting polymer matrix has the added advantage of being able to electrically connect the filler units that do not touch one another, thereby enhancing the connectivity.

Cement is slightly conducting, so the use of a cement matrix also allows the conductive filler units in the composite to be electrically connected, even when the filler units do not touch one another. Thus, cement-matrix composites have higher shielding effectiveness then corresponding polymer-matrix composites in which the polymer matrix is insulating.[80] Moreover, cement is less expensive than polymers and cement-matrix composites are useful for the shielding of rooms in a building.[81,82,83] Similarly, carbon is a superior matrix than polymers for shielding due to its conductivity, but carbon-matrix composites are expensive.[84]

A seam in a housing that serves as an EMI shield needs to be filled with an EMI gasket (i.e., a resilient EMI shielding material), which is commonly a material based on an elastomer, such as rubber.[85–98] An elastomer is resilient, but is itself not able to shield, unless it is coated with a conductor (e.g., a metal coating called metallization) or is filled with a conductive filler (typically metal particles). The coating suffers from its poor wear resistance. The use of a conductive filler suffers from the resulting decrease in resilience, especially at a high filler volume fraction that is usually required for sufficient shielding effectiveness. As the decrease in resilience becomes more severe as the filler concentration increases, the use of a filler that is effective even at a low volume fraction is desirable. Therefore, the development of EMI gaskets is more challenging than that of EMI shielding materials in general.

For a general EMI shielding material in the form of a composite material, a filler that is effective at a low concentration is also desirable, although it is not as critical as for EMI gaskets. This is because the strength and ductibility of a composite tend to decrease with increasing filler content when the filler-matrix bonding is poor. Poor bonding is quite common for thermoplastic polymer matrices. Furthermore, a low filler content is desirable due to the greater processability, which decreases with increasing viscosity. In addition, a low filler content is desirable due to the cost saving and weight saving.

In order for a conductive filler to be highly effective, it preferably should have a small unit size (due to the skin effect), a high conductivity (for shielding by reflection and absorption), and a high aspect ratio (for connectivity). Metals are more attractive for shielding than carbons due to their higher conductivity, though carbons are attractive in their oxidation resistance and thermal stability. Fibers are more attractive than particles due to their high aspect ratio. Thus, metal fibers of a small diameter are desirable. Nickel filaments of diameter 0.4 μm have been shown to be particularly effective.[98,99,100] Nickel is more attractive than copper due to its superior oxidation resistance. The oxide film is poor in conductivity and is thus detrimental to the connectivity among filler units.

Continuous fiber polymer-matrix structural composites that are capable of EMI shielding are needed for aircrafts and electronic enclosures.[84,101–109] The fibers in there composites are typically carbon fibers, which may be coated with a metal (e.g., nickel[110]) or be intercalated (i.e., doped) to increase the conductivity.[111,112]

An alternate design involves the use of glass fibers (not conducting) and conducting interlayers in the composite.[113,114]

4. Emerging materials for shielding

A particularly attractive EMI gasket material is flexible graphite, which is a flexible sheet made by compressing a collection of exfoliated graphite flakes (called worms) without a binder. During exfoliation, an intercalated graphite (graphite compound with foreign species called the intercalate between some of the graphite layers) flake expands typically by over 100 times along the *c*-axis. Compression of the resulting worms (like accordions) causes the worms to be mechanically interlocked to one another, so that a sheet is formed without a binder.

Due to the exfoliation, flexible graphite has a large specific surface area (*e.g.*, 15 m^2/g). Due to the absence of a binder, flexible graphite is essentially entirely graphite (other than the residual amount of intercalate in the exfoliated graphite). As a result, flexible graphite is chemically and thermally resistant, and low in coefficient of thermal expansion. Due to its microstructure involving graphite layers that are preferentially parallel to the surface of the sheet, flexible graphite is high in electrical and thermal conductivities in the plane of the sheet. Due to the graphite layers being somewhat connected perpendicular to the sheet (*i.e.*, the honeycomb microstructure of exfoliated graphite), flexible graphite is electrically and thermally conductive in the direction perpendicular to the sheet (although not as conductive as the plane of the sheet). These in-plane and out-of-plane microstructures result in resilience, which is important for EMI gaskets. Due to the skin effect, a high surface is desirable for shielding. As the electrical conductivity (especially that in the plane of the sheet) and specific surface area are both quite high in flexible graphite, the effectiveness of this material for shielding is exceptionally high (up to 130 dB at 1 GHz).[115]

Other emerging materials for EMI shielding include woodceramics (porous carbons made by impregnating woody materials with phenol resin)[116,117] and aluminum honeycomb.[118]

5. Conclusions

Materials for EMI shielding are mainly electrically conducting materials in the form of metals in bulk, porous, and coating forms; composite materials with polymer; cement and carbon matrices; and carbons. In particular, EMI gasket materials, which require resilience, include elastomers and flexible graphite.

Acknowledgment

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