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Combined Use of Magnetic and Electrically Conductive Fillers in a Polymer Matrix for Electromagnetic Interference Shielding

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The combined use of a highly magnetic filler (mumetal) in low proportion and a highly conductive filler in high proportion in a polymer matrix provides a composite material that is more effective for electromagnetic interference shielding than the use of a highly magnetic filler alone or the use of a highly conductive filler alone. Mumetal is effective (due to absorption) when it is in a composite material of DC electrical resistivity below 10 Ω cm, as provided by conductive fillers, which contribute to shielding by reflection and allow paths for eddy current.

Key words: Electromagnetic, shielding, EMI, polymer, composite, magnetic, electrical resistivity, nickel, mumetal, graphite

INTRODUCTION

Electromagnetic interference (EMI) shielding refers to the blocking of electromagnetic radiation so that the radiation essentially cannot pass through the blocking medium (or shield). Due to the interference of computers and other electronics by radiofrequency radiation (such as that emitted by a cellular phone), there is a growing need for developing materials for such shielding.

The main mechanisms of shielding are reflection and absorption. Electrical conductors such as metals and carbons mainly shield by reflection of the radiation. On the other hand, magnetic materials mainly shield by absorption of the radiation.

Most materials used for shielding are chosen due to their electrical conductivity rather than their magnetic behavior. Indeed, high levels of shielding effectiveness have been attained by the use of electrically conductive materials. For example, a shielding effectiveness of 130 dB at 1 GHz has been attained in a form of sheet graphite known as flexible graphite.[1] The shielding in graphite is due to reflection.[2] Metals in sheet and coating forms are widely used for shielding due to their electrical conductivity and the associated high shielding effectiveness.[3,4]

In spite of the dominance of electrically conductive materials among materials for EMI shielding, magnetic materials are also used for this purpose. In particular, polymer–matrix composites containing soft-magnetic powder have been described in numerous patents for use in EMI shielding.[5–17] Furthermore, a soft-magnetic material together with an electrical conductor in the form of a support (or an adjoining layer) is a configuration that has been reported in patents for use in EMI shielding.[18–21]

This paper is aimed at investigating the effectiveness of magnetic materials and of combinations of magnetic and electrically conductive materials for EMI shielding. For the sake of comparison, this paper includes a study of the effectiveness of electrically conductive materials for shielding. The combination of magnetic and electrically conductive materials is of interest for shielding, due to the electrical conductivity allowing the flow of eddy current induced by the magnetic field that is imparted by the magnetic component. This flow provides a mechanism for the absorption of the radiation.

The magnetic material may be electrically conductive; an electrically conductive material may be

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magnetic. In order to distinguish between the effects of magnetic and electrically conductive materials, this paper uses a highly magnetic material (namely mumetal,[22–24] a nickel-iron alloy with composition 75% nickel, 15% iron, plus copper and molybdenum, and with very high magnetic permeability) as the magnetic component and includes both magnetic and nonmagnetic electrical conductors as choices for the electrically conductive component. A nonmagnetic electrical conductor is graphite; a magnetic conductor is nickel. Nickel is much less magnetic than mumetal, but is more electrically conductive than both mumetal and graphite. Carbon[2] and nickel[25] have long been used for EMI shielding. Mumetal has long been used for magnetic shielding,[26–28] but its use for EMI shielding is limited.[29] In particular, mumetal has not been previously investigated for use as a filler in a composite material for EMI shielding.

For the purpose of understanding the origin of the shielding, this work includes measurements of both the electrical resistivity (DC) and the shielding effectiveness (1 GHz). Although the resistivity is DC rather than AC, it is valuable for indicating the effect of a filler on the electrical conductivity.

A large variety of polymers have been used as matrices for composites for shielding. This work uses acrylic latex as the polymer matrix, due to its availability in the form of water-based particulate dispersions, the convenience of incorporation of the magnetic/conductive fillers in a dispersion by mixing, and the suitability of the use of the resulting dispersion as a coating material (i.e., a paint). Hence, this work is partly aimed at developing a paint for EMI shielding. The paint is expected to be useful for forming coatings on walls, floors, doors, enclosures, aircraft, etc.

EXPERIMENTAL METHODS

Materials

The latex paint was a water-based dispersion of 100% acrylic latex particles. The dispersion is comprised of 10 wt.% to 20 wt.% acrylic polymer and 50 wt.% to 60 wt.% water. It was obtained as DULUX (2201-0100) latex paint from ICI Paints (Cleveland, OH). Its density is 1.21 g/cm^3.

Two types of nickel powder were used, namely nickel powder I and nickel powder II. Nickel powder I was obtained from INCO (Toronto, ON, Canada) with a density of 8.9 g/cm^3 and a particle size ranging from 0.3 μm to 0.5 μm. Nickel powder II was obtained from Novamet (Wyckoff, NJ) with a density of 8.9 g/cm^3 and a particle size ranging from 14 μm to 20 μm.

Nickel flake was obtained from Novamet (Wyckoff, NJ) with a density of 8.9 g/cm^3. It had an irregular platelet shape with an aspect ratio of 20. The thickness was 1 μm and the diameter ranged from 14 μm to 20 μm.

Mumetal powder was prepared by filing a mumetal sheet, which was obtained as CO-NETIC B (stress annealed) from Magnetic Shield Corp. (Bensenville, IL), with a density of 8.7 g/cm^3, a maximum relative magnetic permeability of 1.5×10^5, and a resistivity of 4.8×10^{-5} Ω cm. The particle size of the sieved powder ranged from 28 μm to 40 μm.

The graphite flake used was natural crystalline flake containing at least 98.5 wt.% carbon, of typical size 5 μm, as obtained as Micro 850 from Asbury Graphite Mills, Inc. (Asbury, NJ).

Testing

The attenuation upon reflection and that upon transmission were measured using the coaxial cable method (transmission line method). The attenuation upon transmission is the same as the shielding effectiveness. The coaxial cable method set-up consisted of an Elgal (Israel) SET 19A shielding effectiveness tester with its input and output connected to a Hewlett-Packard (HP) 8752C network analyzer. Figure 1 shows the set-up for shielding effectiveness measurement. An HP APC-7 calibration kit was used to calibrate the system. The frequency was up to 1.5 GHz, as limited by the specimen dimensions. The frequency was scanned from 300 MHz to 1.5 GHz, such that 800 data points were collected within this frequency range. The specimen placed in the center plane of the tester (with the input and output of the tester on the two sides of the specimen) was in the form of an annular ring of outer diameter 97 mm and inner diameter 29 mm. Silver paint was applied at both inner and outer edges of each specimen and at the vicinity of the edges in order to make electrical contact with the inner and outer conductors of the tester.

The various fillers and latex paint in various ratios by volume were mixed by hand. The resulting coating was applied on one side of a Mylar sheet (60 μm), which had been cut to be an annular ring of the dimensions mentioned above. After drying in air

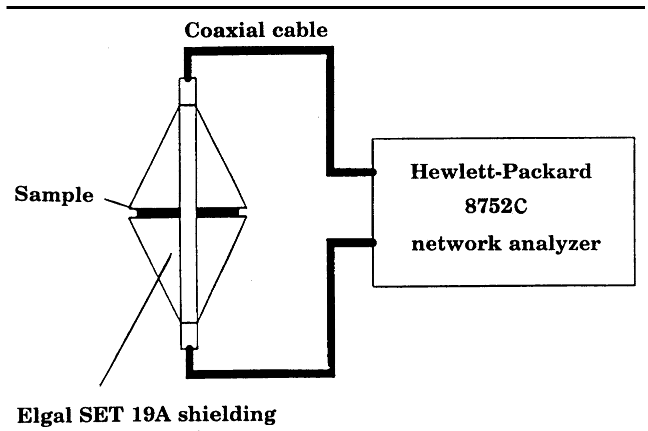

Fig. 1. Set-up for measuring the electromagnetic interference shielding effectiveness.

for at least 2 h, silver paint was applied, as mentioned above. Mylar sheet was chosen as the substrate material due to its electromagnetic transparency. The coating thickness was 0.1 mm to 0.2 mm after drying. Three specimens of each type of coating were tested.

The DC electrical resistivity was measured by using the four-probe method, using silver paint in conjunction with copper wire for electrical contacts. The specimen was of size 80 mm $\times$ 3 mm $\times$ 1 mm. The outer two probes were for passing current; the inner two probes were for voltage measurement. The distance between the two current probes ranged from 68 mm to 72 mm. The distance between the voltage probes ranged from 58 mm to 62 mm. All dimensions (including the thickness) were measured separately for each specimen. Four specimens of each type were tested.

RESULTS

Table I shows the attenuation upon transmission (i.e., shielding effectiveness) and attenuation upon reflection for various compositions in the frequency range from 300 MHz to 1.5 GHz. The ± values shown in Table I indicate the standard deviation from the mean value in the variation with the frequency. Table II shows the values at 1 GHz, with the ± values showing the standard deviation in the variation among specimens of the same type. The Mylar substrate (row 1, Tables I and II) is electromagnetically transparent, exhibiting low attenuation upon transmission (i.e., low shielding effectiveness) and high attenuation upon reflection (i.e., low reflectivity). The base latex paint (row 2, Tables I and II) has similar EMI shielding properties to the Mylar substrate (low shielding effectiveness and low reflectivity). Both the Mylar substrate and base latex paint are transparent to the electromagnetic wave. Consistent with this behavior is their low conductivity.

The use of mumetal as the sole filler (rows 3–5, Tables I and II) improves the shielding effectiveness and decreases the resistivity slightly, even when the mumetal content is at the maximum (10% by volume of base paint), as limited by mixing. The use of graphite flake as the sole filler (row 6, Tables I and II) is more effective in enhancing the shielding and decreasing the resistivity than the use of mumetal as the sole filler at the same volume fraction (row 5, Tables I and II). The use of mumetal together with graphite flake (row 7, Tables I and II) gives results that are almost the same as the use of graphite flake as the sole filler (row 6, Tables I and II). The use of nickel powder I as the sole filler (row 8, Tables I and II) is less effective for shielding than the use of either graphite flake (row 6, Tables I and II) or mumetal (row 5, Tables I and II) as the sole filler, though the effect on the resistivity is similar. The use of nickel powder I together with mumetal (row 9, Tables I and II) gives results that are close to the use of nickel powder I alone.

The use of nickel powder II as the sole filler (row 10, Tables I and II) is much more effective in enhancing the shielding and decreasing the resistivity than the use of nickel powder I (row 8, Tables I and II), graphite flake (row 6, Tables I and II) or mumetal (row 5, Tables I and II) as the sole filler. Furthermore, nickel powder II can be incorporated at up to 20% by volume of the base paint (row 11, Tables I and II), in contrast to the 10% maximum for nickel powder I, graphite flake or

Table I. EMI Shielding Effectiveness (Attenuation upon Transmission) and Attenuation upon Reflection in the Frequency Range from 300 MHz to 1.5 GHz

Row No.	Material on Mylar (Ratio of Ingredients by Volume)	Attenuation Upon Transmission (dB)	Attenuation Upon Reflection (dB)
1	None	0.7 ± 0.1	22.4 ± 1.0
2	Base paint	1.0 ± 0.2	15.8 ± 1.0
3	Base paint + mumetal (100:2)	3.6 ± 0.3	16.2 ± 0.8
4	Base paint + mumetal (100:5)	5.5 ± 0.4	9.8 ± 0.6
5	Base paint + mumetal (100:10)[a]	6.9 ± 0.4	6.8 ± 0.4
6	Base paint + graphite flake (100:10)[a]	8.5 ± 0.5	6.2 ± 0.5
7	Base paint + graphite flake + mumetal (100:10:2)	9.0 ± 0.6	6.4 ± 0.5
8	Base paint + nickel powder I (100:10)[a]	6.4 ± 0.6	7.9 ± 0.3
9	Base paint + nickel powder I + mumetal (100:10:2)	6.2 ± 0.6	8.2 ± 0.4
10	Base paint + nickel powder II (100:10)	17.5 ± 0.6	3.9 ± 0.1
11	Base paint + nickel powder II (100:20)[a]	27.8 ± 0.7	1.8 ± 0.1
12	Base paint + nickel powder II + mumetal (100:20:2)	30.2 ± 0.6	2.2 ± 0.1
13	Base paint + nickel flake (100:10)	26.8 ± 0.7	2.4 ± 0.2
14	Base paint + nickel flake (100:20)[a]	33.7 ± 0.8	1.6 ± 0.1
15	Base paint + nickel flake + mumetal (100:20:2)	39.6 ± 0.9	1.7 ± 0.1

[a]Maximum possible filler content.

Table II. EMI Shielding Effectiveness (Attenuation upon Transmission) at 1 GHz, Attenuation upon Reflection at 1 GHz and DC Electrical Resistivity

Row No.	Material on Mylar (Ratio of Ingredients by Volume)	Attenuation Upon Transmission (dB)	Attenuation Upon Reflection (dB)	Resistivity (Ω cm)
1	None	0.7 ± 0.1	21.6 ± 0.8	10^{18} [a]
2	Base paint	1.3 ± 0.2	16.8 ± 0.9	10^{14}
3	Base paint + mumetal (100:2)	3.2 ± 0.3	15.9 ± 0.8	33.0 ± 1.6
4	Base paint + mumetal (100:5)	5.3 ± 0.4	8.9 ± 0.6	27.8 ± 0.9
5	Base paint + mumetal (100:10)[b]	6.9 ± 0.3	6.4 ± 0.4	25.4 ± 0.8
6	Base paint + graphite flake (100:10)[b]	8.5 ± 0.4	5.6 ± 0.5	22.0 ± 1.0
7	Base paint + graphite flake + mumetal (100:10:2)	8.8 ± 0.5	5.7 ± 0.5	22.5 ± 0.8
8	Base paint + nickel powder I (100:10)[b]	5.8 ± 0.4	7.7 ± 0.5	23.5 ± 1.2
9	Base paint + nickel powder I + mumetal (100:10:2)	5.6 ± 0.3	7.9 ± 0.4	25.3 ± 0.9
10	Base paint + nickel powder II (100:10)	16.2 ± 0.5	3.9 ± 0.1	8.3 ± 0.3
11	Base paint + nickel powder II (100:20)[b]	26.2 ± 0.6	1.8 ± 0.1	4.7 ± 0.3
12	Base paint + nickel powder II + mumetal (100:20:2)	29.3 ± 0.5	1.9 ± 0.1	4.9 ± 0.4
13	Base paint + nickel flake (100:10)	25.7 ± 0.6	2.6 ± 0.2	4.3 ± 0.3
14	Base paint + nickel flake (100:20)[b]	32.4 ± 0.5	1.5 ± 0.1	3.4 ± 0.2
15	Base paint + nickel flake + mumetal (100:20:2)	38.5 ± 0.7	1.6 ± 0.1	3.5 ± 0.3

[a]From DuPont's datasheet for Mylar; [b]Maximum possible filler content.

mumetal. Increasing the nickel powder II content from 10% (row 10, Tables I and II) to 20% (row 11, Tables I and II) by volume of the base paint greatly enhances the shielding effectiveness (from 16 dB to 26 dB), while the resistivity is decreased (from 8.3 Ω cm to 4.7 Ω cm). The use of nickel powder II together with mumetal (row 12, Tables I and II) further increases the shielding effectiveness (from 26 dB to 29 dB), while the resistivity is essentially not affected.

The use of nickel flake as the sole filler (rows 13 and 14, Tables I and II) is even more effective in enhancing the shielding and decreasing the resistivity than the use of nickel powder II as the sole filler (rows 10 and 11, Tables I and II). The use of nickel flake together with mumetal (row 15, Tables I and II) gives higher shielding effectiveness than the use of nickel flake alone, though the resistivity is essentially not affected by the mumetal addition.

DISCUSSION

As shown in Table I, the standard deviations of both shielding effectiveness and attenuation upon reflection are less than 1 dB within the frequency range studied (300 MHz to 1.5 GHz). This indicates that the frequency is a minor factor in affecting the shielding effectiveness of the various compositions.

The results in Table II indicate that mumetal by itself does not provide high shielding effectiveness, but it is effective in enhancing shielding when the electrical resistivity is low (below 10 Ω cm), as made possible by a conductive filler such as nickel flake or nickel powder II. Even mumetal at 10% by volume of the base paint as the sole filler is much less effective than mumetal at 2% by volume of the base paint in the presence of a conductive filler that renders a sufficiently low resistivity. Mumetal as the sole filler is even less effective for shielding than graphite flake, nickel powder II or nickel flake at the same content of 10% by volume of the base paint. Among these fillers, all used alone, nickel flake is the most effective, both in shielding and conduction, whereas nickel powder I is the least effective for shielding. Nickel powder I is comparable to graphite flake in terms of its effectiveness for conduction, but is less effective than nickel powder II or nickel flake for conduction.

The origin of the differences in effectiveness among the various conductive fillers is not completely clear. The particle size, shape, and surface condition are all factors that affect the effectiveness. In particular, larger particles tend to be dispersed more easily, thus resulting in better connectivity among the particles and hence lower resistivity and higher shielding effectiveness. This is probably why nickel powder II is more effective than nickel powder I at the same loading. This is also why the maximum loading is higher for nickel powder II than it is for nickel powder I. Furthermore, a higher aspect ratio promotes connectivity, thereby causing nickel flake to be more effective than nickel powder II.

In the presence of a conductive filler, mumetal addition essentially does not affect the resistivity or the attenuation upon reflection, but increases the shielding effectiveness. This means that mumetal enhances shielding by absorption. In contrast, conductive filler addition (in the absence of mumetal) decreases both the resistivity and the attenuation upon reflection, while enhancing shielding. This means that the conductive filler enhances shielding by reflection.

In the absence of a conductive filler, mumetal addition greatly decreases both the resistivity and the attenuation upon reflection, while enhancing shielding, such that all effects become more significant as the mumetal content increases. This suggests that mumetal as the sole filler enhances shielding mainly by reflection, in spite of the high magnetic permeability of mumetal.

This work shows that mumetal is valuable for EMI shielding only in the presence of a material that renders high electrical conductivity to the composite. In this situation, the shielding provided by the mumetal is by absorption, while that provided by the conductive component is by reflection. This finding is consistent with the notion that eddy current, as enhanced by a high conductivity medium, provides a mechanism for absorption of electromagnetic radiation. It is also consistent with the theory of EMI shielding, as discussed below.

The shielding effectiveness ($S.E.$) of a material under the interference of an ambient electromagnetic wave is expressed as[30]

$$S.E. = R + A + B, \tag{1}$$

where $S.E.$ is the shielding effectiveness in dB, R is the reflection loss in dB, A is the absorption loss in dB, and B is the correction factor due to multiple reflections within the material. For a plane electromagnetic field, the reflection loss R can be explained as[31]

$$R = 168.2 + 10\log_{10}\frac{\sigma_\mathrm{r}}{\mu_\mathrm{r} f} \tag{2}$$

and the absorption loss A can be expressed as[31]

$$A = 0.1314\, t\sqrt{\mu_\mathrm{r}\sigma_\mathrm{r} f}. \tag{3}$$

The correction factor B can be expressed as[31]

$$\begin{aligned} B &= 20\log_{10}\left|1-\left(\frac{(K-1)^2}{(K+1)^2}\right)\left(10^{-A/10}\right)\left(\mathrm{e}^{-0.227\cdot Aj}\right)\right| \\ &= 20\log_{10}\left|1-\left(\frac{(K-1)^2}{(K+1)^2}\right)\left(10^{-0.013\,t\sqrt{\mu_\mathrm{r}\sigma_\mathrm{r} f}}\right)\right. \\ &\qquad \left.\times\left(\mathrm{e}^{-0.03\,t\sqrt{\mu_\mathrm{r}\sigma_\mathrm{r} f}\cdot j}\right)\right| \end{aligned} \tag{4}$$

where $j = \sqrt{-1}$.

With the use of Eqs. 1–4, the theoretical shielding effectiveness can be expressed as

$$\begin{aligned} S.E. &= 168.2 + 10\log_{10}\frac{\sigma_\mathrm{r}}{\mu_\mathrm{r} f} + 0.1314\, t\sqrt{\mu_\mathrm{r}\sigma_\mathrm{r} f} \\ &\quad + 20\log_{10}\left|1-\left(\frac{(K-1)^2}{(K+1)^2}\right)\left(10^{-0.013\,t\sqrt{\mu_\mathrm{r}\sigma_\mathrm{r} f}}\right)\right. \\ &\qquad \left.\times\left(\mathrm{e}^{-0.03\,t\sqrt{\mu_\mathrm{r}\sigma_\mathrm{r} f}\cdot j}\right)\right| \end{aligned} \tag{5}$$

where σ_r is the electrical conductivity relative to copper, μ_r is the permeability relative to free space, f is the frequency in Hz, and t is the thickness of the material in millimeters. The quantity K in Eq. 5 is defined as

$$K = Z_s/Z_H, \tag{6}$$

where Z_s is the intrinsic impedance of the shielding material, and Z_H is the intrinsic impedance of the medium in which the incident electromagnetic wave travels.

Assuming that there is no multiple reflection within the material, Eq. 5 can be written as

$$S.E. = 168.2 + 10\log_{10}\frac{\sigma_\mathrm{r}}{\mu_\mathrm{r}} + 0.1314\, t\sqrt{\mu_\mathrm{r}\sigma_\mathrm{r} f}. \tag{7}$$

Given that the resistivity of copper is 1.678×10^{-6} Ω cm, f is 1 GHz, and the average thickness of the coating is 0.15 mm, Eq. 7 becomes

$$\begin{aligned} S.E. &= 168.2 + 10\log_{10}\frac{1.678\times10^{-6}}{\mu_\mathrm{r}10^9\rho} + 0.134\times0.15 \\ &\quad \times\sqrt{\frac{\mu_\mathrm{r}\times1.678\times10^{-6}\times10^9}{\rho}}, \end{aligned} \tag{8}$$

where ρ is the resistivity of the shielding material. Hence,

$$S.E. = 2.4 - 10\log_{10}(\mu_\mathrm{r}\rho) + 0.8\sqrt{\frac{\mu_\mathrm{r}}{\rho}}. \tag{9}$$

In general, $S.E.$ depends on ρ and μ_r, so that

$$d(S.E.) = \frac{\partial(S.E.)}{\partial\rho}d\rho + \frac{\partial(S.E.)}{\partial\mu_\mathrm{r}}d\mu_\mathrm{r}. \tag{10}$$

From Eq. 9,

$$\frac{\partial(S.E.)}{\partial\mu_\mathrm{r}} = -10\frac{1}{\ln(10)\mu_\mathrm{r}} + \frac{0.8}{\sqrt{\rho}}\frac{1}{2\sqrt{\mu_\mathrm{r}}} = \frac{0.4}{\sqrt{\rho\mu_\mathrm{r}}} - \frac{4.34}{\mu_\mathrm{r}} \tag{11}$$

and

$$\frac{\partial(S.E.)}{\partial\rho} = -10\frac{1}{\ln(10)\rho} - \frac{0.8\sqrt{\mu_\mathrm{r}}}{\rho^{1.5}} = \frac{4.34}{\rho} - \frac{0.8\sqrt{\mu_\mathrm{r}}}{\rho^{1.5}}, \tag{12}$$

where ρ is the resistivity of material in Ω cm.

For a polymer that is filled with nonmagnetic conductive particles, such as graphite flake (row 7, Table I), Eq. 9 gives

$$S.E. = 20.4 - 10\log_{10}(22.0) + 0.8\sqrt{\frac{1}{22.0}} = 9.1\ \text{dB}.$$

This value of 9.1 dB is quite close to the measured shielding effectiveness of 8.5 dB.

In this work, it was found that using mumetal powder as the secondary filler did not have a significant effect on the resistivity of the composite (rows 6 and 7 in comparison, rows 8 and 9 in comparison, rows 11 and 12 in comparison, and rows 14 and 15 in comparison, all in Table I). Therefore, it is reasonable to assume that $d\rho$ is zero. Therefore, with the help of Eq. 11, Eq. 10 can be written as

$$d(S.E.) = \left(\frac{0.4}{\sqrt{\rho\mu_r}} - \frac{4.34}{\mu_r}\right)d\mu_r. \quad (13)$$

The relative permeability μ_r of a composite is increased by using mumetal powder as the secondary filler. In order to improve the shielding effectiveness of the composite, the first term on the right-hand side of Eq. 13 must be positive. Hence,

$$\left(\frac{0.4}{\sqrt{\rho\mu_r}} - \frac{4.34}{\mu_r}\right) > 0. \quad (14)$$

Rearrangement of Eq. 14 gives

$$\mu_r > 117.7\ \rho. \quad (15)$$

Equation 15 indicates that the addition of mumetal as the magnetic component can improve the shielding effectiveness significantly only when the material exhibits low resistivity. This is consistent with the experimental results of this paper.

The level of shielding required in practice depends on the application. For buildings, a shielding effectiveness of 20 dB is usually adequate, though a much higher value is desired for military applications, such as the deterring of electromagnetic spying.

In this work, 20 vol.% of nickel powder is the maximum feasible loading. The use of nickel-plated graphite powder may be an alternate scheme that is attractive for reducing the weight of the shielding material.

The highest level of shielding attained in this work is 39 dB at 1 GHz (Table II). This value is higher than the value of 34 dB at 1 GHz previously reported for a coating of similar thickness but in the form of a water-based dispersion comprising discontinuous stainless steel fiber (8 μm diameter), 5 μm graphite flake, and submicron graphite flake.[32] Without the steel fiber in the dispersion, the shielding effectiveness is only 28 dB. The effectiveness of the steel fiber is attributed mainly to its small diameter (the skin effect), although the large aspect ratio of the fiber may help the electrical connectivity and the limited magnetic character of the steel may help the shielding through absorption. In contrast, the mumetal powder used in this work is large in particle size, low in aspect ratio, and high in magnetic permeability. Thus, this work is designed to addresses the effect of a magnetic filler, whereas Ref. 32 is not.

Reference 32 and this work also differ in the vehicle used in the dispersion. Reference 32 uses water as the vehicle, whereas this work uses a polymer as the vehicle. A water-based dispersion[32] has the advantage of the evaporation of the water from the coating after coating application causing an increased degree of direct contact between the conductive fiber and flake. However, in spite of the small amount of binder in a water-based dispersion, the coating is mechanically weak and the adhesion of the coating is also relatively weak, compared to the polymer-based coating of this work.

CONCLUSION

Mumetal is an effective filler in a polymer for enhancing EMI shielding when it is in a composite material of DC electrical resistivity below 10 Ω cm, as provided by conductive fillers such as nickel flake or nickel powder II. The shielding provided by the mumetal is by absorption, while that provided by the conductive fillers is reflection. In the absence of a conductive filler that provides resistivity below 10 Ω cm to the composite, mumetal is not effective for shielding. By using mumetal at 2% by volume of the base latex paint and nickel flake at 20% by volume of the base paint, a paint exhibiting a shielding effectiveness of 39 dB at 1 GHz has been attained.

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