PERGAMON

Carbon 39 (2001) 279–285

CARBON

Review

# Electromagnetic interference shielding effectiveness of carbon materials

D.D.L. Chung*

*Composite Materials Research Laboratory, State University of New York at Buffalo, Buffalo, NY 14260-4400, USA*

Received 23 March 2000; accepted 22 July 2000

## Abstract

Carbon materials for electromagnetic interference (EMI) shielding are reviewed. They include composite materials, colloidal graphite and flexible graphite. Carbon filaments of submicron diameter are effective for use in composite materials, especially after electroplating with nickel. Flexible graphite is attractive for EMI gaskets.

*Keywords:* A. Carbon composites, Carbon fibers, Carbon filaments, Exfoliated graphite; D. Electrical properties

## 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) tend to interfere with electronics (e.g. computers), EMI shielding of both electronics and 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].

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.

EMI shielding is a rapidly growing application of carbon materials, especially discontinuous carbon fibers. This review addresses carbon materials for EMI shielding, including non-structural and structural composites, colloidal graphite, as well as EMI gasket materials.

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

---

*Tel.: +1-716-645-2593; fax: +1-716-645-3875.

*E-mail address:* ddlchung@acsu.buffalo.edu (D.D.L. Chung).

0008-6223/01/$ – see front matter

PII: S0008-6223(00)00184-6

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 $\sigma_r/\mu_r$, where $\sigma_r$ is the electrical conductivity relative to copper and $\mu_r$ is the relative magnetic permeability. 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 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 ($\delta$), which is given by

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

where $f$ = frequency, $\mu$ = magnetic permeability = $\mu_0 \mu_r$, $\mu_r$ = relative magnetic permeability, $\mu_0 = 4\pi \times 10^{-7}$ H m$^{-1}$, and $\sigma$ = electrical conductivity in $\Omega^{-1}$ m$^{-1}$.

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

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 than corresponding polymer–matrix composites in which the polymer matrix is insulating [80]. A shielding effectiveness of 40 dB at 1 GHz has been attained in a cement–matrix composite containing just 1.5 vol.% discontinuous 0.1 μm-diameter carbon filaments [80]. Moreover, cement is less expensive than polymers and cement–matrix composites are useful for the shielding of rooms in a building [81–83]. 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 (relative to the skin depth), a high conductivity (for shielding by reflection) and a high aspect ratio (for connectivity). Fibers are more attractive than particles due to their high aspect ratio.

EMI shielding is one of the main applications of conventional short carbon fibers [99]. Due to the small diameter, carbon filaments (catalytically grown, of diameter 0.1 μm) are more effective at the same volume fraction in a composite than conventional short carbon fibers for EMI shielding, as shown for both thermoplast [54,100] and cement [80,101] matrices. For example, in a thermoplast matrix, carbon filaments at 19 vol.% give an EMI shielding effectiveness of 74 dB at 1 GHz [100], whereas carbon fibers (isotropic pitch based, 3000 μm long) at 20 vol.% give a shielding effectiveness of 46 dB at 1 GHz [54]. In a cement–matrix composite, fiber volume fractions are typically less than 1%. Carbon filaments at 0.54 vol.% in a cement paste give an effectiveness of 26 dB at 1.5 GHz [80], whereas carbon fibers (isotropic pitch based, 3 mm long) at 0.84 vol.% in a mortar give an effectiveness of 15 dB at 1.5 GHz [101]. These effectiveness measurements were made with the same fixture and about the same sample thickness.

Metals are more attractive for shielding than carbons due to their higher conductivity, though carbons are attractive in their oxidation resistance and thermal stability. Thus, metal fibers of a small diameter are most desirable, though metal fibers made by forming or casting typically cannot be finer than about 2 μm. However, submicron diameter metal fibers can be made by coating submicron diameter carbon filaments with a metal. Nickel filaments of diameter 0.4 μm, as made by electroplating 0.1 μm-diameter carbon filaments with nickel, have been shown to be particularly effective [98,100,101]. They are known as nickel filaments because they are mostly nickel rather than carbon. A shielding effectiveness of 87 dB at 1 GHz has been attained in a polymer–matrix composite containing just 7 vol.% nickel filaments. Nickel is more attractive than copper, partly due to its superior oxidation resistance. The oxide film is poor in conductivity and is thus detrimental to the connectivity among filler units.

Table 1 compares the EMI shielding effectiveness at 1–2 GHz of polyethersulfone (PES)–matrix composites with various fillers at the same sample thickness of 2.8 mm. The shielding effectiveness for all specimens was determined by the coaxial cable method using the same tester. Even at a low filler content of 7 vol.%, the nickel filaments provide much greater shielding effectiveness than all the other fillers of Table 1. In the case of the matrix being polyimidesiloxane (PISO) instead of PES, nickel particles of size 1–5 μm provide greater EMI shielding effectiveness at 1–2 GHz than silver particles of size 0.8–1.35 μm [57]. Together with Table 1, this means that nickel filaments provide greater shielding effectiveness than silver particles.

Table 1
Electromagnetic interference shielding effectiveness at 1–2 GHz of PES–matrix composites with various fillers

| Filler | Vol.% | EMI shielding effectiveness (dB) | Ref. |
|---|---|---|---|
| Al flakes (15×15×0.5 μm) | 20 | 26 | [54] |
| Steel fibers (1.6 μm dia.×30~56 μm) | 20 | 42 | [54] |
| Carbon fibers (10 μm dia.×400 μm) | 20 | 19 | [54] |
| Ni particles (1~5 μm dia.) | 9.4 | 23 | [56] |
| Ni fibers (20 μm dia.×1 mm) | 19 | 5 | [100] |
| Ni fibers (2 μm dia.×2 mm) | 7 | 58 | [100] |
| Carbon filaments (0.1 μm dia.×>100 μm) | 7 | 32 | [100] |
| Ni filaments (0.4 μm dia.×>100 μm) | 7 | 87 | [100] |

The submicron diameter filaments mentioned above are discontinuous and are thus not sufficient for providing structural composites [54,80,100]. Continuous fiber polymer–matrix structural composites that are capable of EMI shielding are needed for aircraft and electronic enclosures [84,102–111]. The fibers in these composites are typically carbon fibers (of diameter around 10 μm), which may be coated with a metal (e.g. nickel [112]) or be intercalated (i.e. doped) to increase the conductivity [113,114].

## 4. Flexible graphite 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 $m^2 g^{-1}$). 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 (CTE). 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 resembling an accordion), 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 area 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].

## 5. Colloidal graphite

Colloidal graphite is a fine graphite powder suspended in a liquid carrier (such as water and alcohol), together with a small amount of a polymeric binder. After application of colloidal graphite on a surface by painting or other methods, the liquid carrier evaporates, thus allowing the graphite particles to be essentially in direct contact. The resulting coating is effective for EMI shielding. It is commonly used for shielding in television scopes.

## 6. Conclusion

Carbon materials for EMI shielding are mainly carbon fiber composites, colloidal graphite and flexible graphite. The composites include non-structural composites with discontinuous fibers and structural composites with continuous fibers. Carbon filaments of submicron diameter, as made catalytically from carbonaceous gases, are effective, especially after electroplating with nickel. Flexible graphite is attractive for EMI gaskets.

## Acknowledgements

This work was supported by Defense Advanced Research Projects Agency, USA

## References

[1] Bjorklof D. EMC fundamentals. Part Six: EMI filters and transient. Compliance Engineer 1998;15(5):10.
[2] Brewer R, Fenical G. Shielding: The hole problem. Evaluation Engineer 1998;37(7):S4–S10.
[3] O'Shea P. How to meet the shielding needs of a 500-MHz PC. Evaluation Engineer 1998;37(6):40, 43, 45–46.
[4] Devender, Ramasamy SR. Review of EMI shielding and suppression materials. Proc. Int. Conf. Electromagnetic Interference and Compatibility 1997. IEEE, Piscataway (New Jersey, USA): IEEE 1997;459–466.
[5] Geddes B. Putting a lid on EMI/RFI. Control (Chicago, Ill) 1996;9(10):4.
[6] Hempelmann S. Surface engineering for EMI compliance. Process and practical examples. Galvanotechnik 1997;88(2):418–24.
[7] Kimmel WD, Gerke DD. Controlling EMI with cable shields. Medical Device & Diagnostic Industry 1995;17(7):112–5.
[8] Markstein HW. Effective shielding defeats EMI. Electronic Packaging & Production 1995;35(2):4.
[9] McRae KA. Electromagnetic shielding in today's environment. National Conf. Publication – Institution of Engineers, Australian, Vol. 2, No. 94/11, IE Aust, Crows Nest, NSW, Aust. 1994;495–498.
[10] Sadchikov VV, Prudnikova ZG. Amorphous materials in electromagnetic shields. Stal' 1997;4:66–9.
[11] Shinagawa S, Kumagai Y, Urabe K. Conductive papers containing metallized polyester fibers for electromagnetic interference shielding. J Porous Mater 1999;6(3):185–90.
[12] Jackson BC, Shawhan G. In: IEEE Int. Symp. Electromagnetic Compatibility, Current review of the performance characteristics of conductive coatings for EMI control, vol. 1, Piscataway, New Jersey, USA: IEEE, 1998, pp. 567–72.
[13] Kumar R, Kumar A, Kumar D. In: Proc. Int. Conf. Electromagnetic Interference and Compatibility, IEEE, Piscataway, RFI/EMI/microwave shielding behaviour of metallized fab-

ric – a theoretical approach, New Jersey, USA: IEEE, 1997, pp. 447–50.

[14] Bhatgadde LG, Joseph S. In: Proc. Int. Conf. Electromagnetic Interference and Compatibility, IEEE, Piscataway, New Jersey, USA: IEEE, 1997, pp. 443–5.

[15] Sidhu A, Reike J, Michelsen U, Messinger R, Habiger E, Wolf J. In: IEEE Int. Symp. Electromagnetic Compatibility, IEEE, Piscataway, Metallization of plastics for shielding, New Jersey, USA: IEEE, 1997, pp. 102–5.

[16] Hajdu J. New challenges for electroless plating technologies. Trans Inst Metal Finish 1997;75(pt. 1):B7–B10.

[17] Klemmer G. In: Special Areas, 54th Annual Technical Conf. – ANTEC, Conf. Proc, Shielding approaches, vol. 3, Brookfield, Connecticut, USA: Society of Plastics Engineers, 1996, pp. 3430–2.

[18] Gwinner D, Scheyrer P, Fernandez W. In: Proc. 39th Annual Technical Conf. – Soc. Vacuum Coaters, Selective deposition of aluminum on plastic parts for EMI shielding, Albuquerque, New Mexico, USA: Society of Vacuum Coaters, 1996, p. 336.

[19] Bhatia MS. In: Proc. 1995 4th Int. Conf. Electromagnetic Interference and Compatibility, Technique for depositing metal layers over large areas for EMI shielding, Madras, India: IEEE, 1995, pp. 321–4.

[20] Zhang L, Li W, Liu J, Ren B. Process and performance of electroless Cu/Ni–P double film. Cailiao Gongcheng/J Mater Eng 1995;7:38–41.

[21] Mandich NV. EMI shielding by electroless planting of ABS plastics. Plating & Surface Finish 1994;81(10):60–3.

[22] Jackson BC, Kuzyk P. In: IEE Conf. Publication, No. 396, Practical guide on the use of electroless coatings for EMI shielding, Stevenage, UK: IEEE, 1994, pp. 119–24.

[23] Nagasawa C, Kumagai Y, Urabe K, Shinagawa S. Electromagnetic shielding particleboard with nickel-plated wood particles. J Porous Mater 1999;6(3):247–54.

[24] Dixon DS, Masi J. In: IEEE Int. Symp. Electromagnetic Compatibility, Thin coatings can provide significant shielding against low frequency EMF/magnetic fields, vol. 2, Piscataway, New Jersey, USA: IEEE, 1998, pp. 1035–40.

[25] Mason PJD. In: Proc. 37th Annual Technical Conf. – Soc. Vacuum Coaters, Technologies and markets for thin film EMI/RFI shielding materials, Albuquerque, New Mexico, USA: Society of Vacuum Coaters, 1994, pp. 192–7.

[26] Grimes CA. EMI shielding characteristics of permalloy multilayer thin films. In: IEEE Aerospace Applications Conf. Proc., IEEE, Computer Society Press Los Alamitos, California, USA: IEEE, 1994, pp. 211–21.

[27] Biter WJ, Jamnicky PJ, Coburn W. In: 7th International SAMPE Electronics Conference, Shielding improvement by use of thin multilayer films, vol. 7, Covina, California, USA: SAMPE, 1994, pp. 234–42.

[28] Xing L, Liu J, Ren S. Study on electromagnetic property of short carbon fibers and its application to radar absorbing materials. Cailiao Gongcheng/J Mater Eng 1998;1:19–21.

[29] Rupprecht L, Hawkinson C. Conductive plastics for medical applications. Medical Device & Diagnostic Industry 1999;21(1):8.

[30] Tan S, Zhang M, Zeng H. Electroconductive polymer composite for shielding EMI. Cailiao Gongcheng/J Mater Eng 1998;5:6–9.

[31] Charbonneau R. In: Proc. 43rd Int. SAMPE Symp. Exhib, Development of carbon fiber thermoplastic compounds for EMI/RFI applications in portable and wireless electronics, vol. 43, Covina, California, USA: SAMPE, 1998, pp. 833–44.

[32] Kolyer JM. In: Proc. 43rd Int. SAMPE Symp. Exhib, Environmentally resistant, conductive adhesive bonds for radio frequency (RF) shielding, vol. 43, Covina, California, USA: SAMPE, 1998, pp. 810–22.

[33] Thompson SL. All about ESD plastics. Evaluation Engineering 1998;37(7):62–63, 65.

[34] Olivero DA, Radford DW. Multiple percolation approach to EMI shielding composites incorporating conductive fillers. J Reinforced Plastics & Composites 1998;17(8):674–90.

[35] Sau KP, Chaki TK, Chakraborty A, Khastgir D. Electromagnetic interference shielding by carbon black and carbon fibre filled rubber composites. Plastics Rubber & Composites Processing & Applications 1997;26(7):291–7.

[36] Genetti WB, Grady BP, O'Rear EA. Effect of orientation on electrically conducting polymer composite properties. Electronic Packaging Materials Science IX, Materials Research Society Symp. Proc., Vol. 445. MRS, Warrendale (Pennsylvania, USA): Materials Research Society, 1997;153–158.

[37] Mao J, Chen J, Tu M, Huang W, Liu Y. Effect of binding agent and solidification process on conductive ability of Ni conductive paint. Gongneng Cailiao/J Functional Mater 1997;28(2):137–9.

[38] Rupprecht L. In: Proc. 2nd Conf. Plastics for Portable and Wireless Electronics, Predicting shielding effectiveness of conductive thermoplastic materials, Brookfield. Connecticut, USA: Society of Plastics Engineers, 1996, pp. 12–20.

[39] Bachman BK. In: Proc. 2nd Conf. Plastics for Portable and Wireless Electronics, Flexible conductive coatings on thermoformed films for EMI/RFI shielding, Brookfield, Connecticut, USA: Society of Plastics Engineers, 1996, pp. 7–11.

[40] Schneider S. Materials for electrostatic discharge and electromagnetic compatibility applications. Kunststoffe Plast Europe 1997;87(4):487–8.

[41] Schneider S. Materials for electrostatic discharge and electromagnetic compatibility applications. Kunstetoffe Plast Europe 1997;87(4):26.

[42] Huang Ch-Y, Pai J-F. Studies on processing parameters and thermal stability of ENCF/ABS composites for EMI shielding. J Appl Polymer Sci 1997;63(1):115–23.

[43] Rosenow MWK, Bell JAE. In: Materials 55th Annual Tech. Conf. – ANTEC, Conf. Proc, Injection moldable nickel coated carbon fiber concentrate for EMI shielding applications, vol. 2, Brookfield, Connecticut, USA: Society of Plastics Engineers, 1997, pp. 1492–8.

[44] Rosenow MWK, Bell JAE. In: Proc. 43rd Int. SAMPE Symp. Exhib, EMI shielding effectiveness of nickel coated carbon fiber as a long fiber thermoplastic concentrate, vol. 43, Covina, California, USA: SAMPE, 1998, pp. 854–64.

[45] Saltzberg MA, Neller AL, Harvey CS, Borninski TE, Gordon RJ. Using polymer thick film for cost-effective EMC protection on PCBs for automotive applications. Circuit World 1996;22(3):67–8.

[46] Wang J, Varadan VV, Varadan VK. EMI shielding with lightweight metal fiber composites. SAMPE J 1996;32(6):18–22.

[47] Masi JV, Dixon DS. In: 7th Int. SAMPE Electronics Conf, Predicting the electromagnetic performance of composite materials, vol. 7, Covina, California, USA: SAMPE, 1994, pp. 243–51.

[48] Rahman H, Dowling J, Saha PK. Application of frequency sensitive surfaces in electromagnetic shielding. J Mater Proc Tech 1995;54(1–4):21–8.

[49] Dani AA, Ogale AA. Electrical percolation in short fiber composites. 50 Years of Progress in Materials and Science Technology, 26th Int. SAMPE Technical Conf., Vol. 26. SAMPE, Covina (California, USA): SAMPE, 1994;689–699.

[50] Radford DW. Volume fraction effects in ultra-lightweight composite materials for EMI shielding. J Adv Mater 1994;26(1):45–53.

[51] Ma CM, Hu AT, Chen DK. Processability, electrical and mechanical properties of EMI shielding ABS composites. Polymers & Polymer Composites 1993;1(2):93–9.

[52] Miyashita K, Imai Y. Study on shielding materials for electromagnetic waves. Int Progr Urethanes 1993;6:195–218.

[53] Li L, Yih P, Chung DDL. Effect of the second filler which melted during composite fabrication on the electrical properties of short fiber polymer–matrix composites. J Electr Mater 1992;21(11):1065–71.

[54] Li L, Chung DDL. Electrical and mechanical properties of electrically conductive polyethersulfone composite. Composites 1994;25(3):215–24.

[55] Li L, Chung DDL. Tin–lead flake polyether sulfone composite formed by in-situ melt processing of tin–lead particles. Polym Compos 1993;14(5):361–6.

[56] Li L, Chung DDL. Effect of viscosity on the electrical properties of conducting thermoplastic composites made by compression molding of a powder mixture. Polym Compos 1993;14(6):467–72.

[57] Li L, Chung DDL. Electrically conducting powder filled polyimidesiloxane. Composites 1991;22(3):211–8.

[58] Zhu M, Chung DDL. Nickel fiber silicone–matrix composites as resilient electrical conductors. J Electron Packag 1991;113:417–20.

[59] Zhu M, Chung DDL. A three-dimensionally interconnected metal spring network in a silicone matrix as a resilient and electrically conducting composite material. Composites 1992;23(5):355–64.

[60] Pomposo JA, Rodriguez J, Grande H. Polypyrrole-based conducting hot melt adhesives for EMI shielding applications. Synth Met 1999;104(2):107–11.

[61] Park J-S, Ryn S-H, Chung O-H. In: 56th Annual Technical Conf. – ANTEC, Conf. Proc, Preparation of conducting composites and studies on some physical properties, vol. 2, Brookfield, Connecticut, USA: Society of Plastics Engineers, 1998, pp. 2410–4.

[62] Courric S, Tran VH. Electromagnetic properties of poly(*p*-phenylene-vinylene) derivatives. Polymer 1998;39(12):2399–408.

[63] Angelopoulos M. In: Proc. 3rd Annual Conf. Plastics for Portable and Wireless Electronics, Conducting polyanilines: properties and applications in microelectronics, Brookfield, Connecticut, USA: Society of Plastics Engineers, 1997, p. 66.

[64] Makela T, Pienimaa S, Taka T, Jussila S, Isotalo H. Thin polyaniline films in EMI shielding. Synth Met 1997;85(1–3):1335–6.

[65] Kohlman RS, Min YG, MacDiarmid AG, Epstein AJ. Tunability of high frequency shielding in electronic polymers. J Engineer Appl Sci 1996;2:1412–6.

[66] Naishadham K. In: 7th Int. SAMPE Electronics Conf, Microwave characterization of polymeric materials with potential applications in electromagnetic interference (EMI) shielding, vol. 7, Covina, California, USA: SAMPE, 1994, pp. 252–65.

[67] Kaynak A, Polat A, Yilmazer U. Some microwave and mechanical properties of carbon fiber–polypropylene and carbon black–polypropylene composites. Mater Res Bull 1996;31(10):1195–206.

[68] Kaynak A. Electromagnetic shielding effectiveness of galvanostatically synthesized conducting polypyrrole films in the 300–2000 MHz frequency range. Mater Res Bull 1996;31(7):845–60.

[69] Joo J, MacDiarmid AG, Epstein AJ. In: 53rd Ann. Tech. Conf. – ANTEC, Conf. Proc, Control of dielectric response of polyanilines: applications to EMI shielding, vol. 2, Brookfield, Connecticut, USA: Society of Plastics Engineers, 1995, pp. 1672–7.

[70] Borgmans CPJH, Glaser RH. Design considerations for EMI shielding conductive plastic compounds. Evaluat Eng 1995;34(7):S32–7.

[71] Yan P. Plastics get wired. Sci Am 1995;273(1):82–7.

[72] Mooney PJ. Status of conductive polymers. JOM 1994;46(3):44–5.

[73] Kuhn HH, Child AD, Kimbrell WC. Toward real applications of conductive polymers. Synth Mat 1995;71(1–3 pt. 3):2139–42.

[74] Nguyen MT, Diaz AF. Novel method for the preparation of magnetic nanoparticles in a polypyrrole powder. Adv Mater 1994;6(11):858–60.

[75] Unsworth J, Conn C, Jin Z, Kaynak A, Ediriweera R, Innis P, Booth N. Conducting polymers: properties and applications. J Intelligent Mater Sys Struc 1994;5(5):595–604.

[76] Kaynak A, Unsworth J, Clout R, Mohan AS, Beard GE. Study of microwave transmission, reflection, absorption, and shielding effectiveness of conducting polypyrrole films. J Appl Polym Sci 1994;54(3):269–78.

[77] Kaynak A, Mohan AS, Unsworth J, Clout R. Plane-wave shielding effectiveness studies on conducting polypyrrole. J Mater Sci Lett 1994;13(15):1121–3.

[78] Sauerer W. Intrinsically conducting polymers – from exploratory research to applications. Galvanotechnik 1994;85(5):1467–72.

[79] de Goefe MP, Steenbakkers LW. Shielding with conductive plastics. Kunststoffe Plast Europe 1994;84:16–8.

[80] Fu X, Chung DDL. Submicron-diameter-carbon-filament cement–matrix composites. Carbon 1998;36(4):459–62.

[81] Gnecco L. Building a shielded room is not construction 101. Evaluat Eng 1999;38(3):3.

[82] Lin S-S. Application of short carbon fiber in construction. SAMPE J 1994;30(5):39–45.

[83] Kurosaki Y, Satake R. In: IEEE Int. Symp. Electromagnetic Compatibility, Relationship between the effectiveness of electromagnetic shielded rooms and the effectiveness of shielding materials, Piscataway, New Jersey, USA: IEEE, 1994, pp. 739–40.

[84] Luo X, Chung DDL. Electromagnetic interference shielding using continuous carbon fiber carbon–matrix and polymer–matrix composites. Composites: Part B 1999;30(3):227–31.

[85] Zhu M, Qiu Y, Tian J. Study of shielding effectiveness for conductive gasket material. Gongneng Cailiao/J Funct Mater 1998;29(6):645–7.

[86] Case DA, Oliver MJ. Method for evaluating EMI/RFI gasket

material in PCMCIA cards. Compliance Eng. 1999;16(2):40,42,44,46,48–49.

[87] Hudak S. Installation and attachment options for EMI gasket. Evaluat Eng 1998;37(8):3.

[88] Prakash BN, Roy LD. In: Proc. 5th Int. Conf. Electromagnetic Interference and Compatibility, Assessment of conductive gaskets using X-ray fluorescence technique, Piscataway, New Jersey, USA: IEEE, 1997, pp. 1–2.

[89] Peng SH, Zhang K. In: 56th Annual Tech. Conf. – ANTEC, Conf. Proc, Finite element analysis aided engineering of elastomeric EMI shielding gaskets, vol. 2, Brookfield, Connecticut, USA: Society of Plastics Engineers, 1998, pp. 1216–8.

[90] Das SK, Nuebel JZB. In: IEEE 14th Int. Symp. Electromagnetic Compatibility, Investigation on the sources of shielding degradation for gaskets with zinc coated steel enclosures, Piscataway, New Jersey, USA: IEEE, 1997, pp. 66–71.

[91] Peng SH, Tzeng WSV. In: IEEE Int. Symp. Electromagnetic Compatibility, Recent developments in elastomeric EMI shielding gasket design, Piscataway, New Jersey, USA: IEEE, 1997, pp. 94–7.

[92] O'Shea P. Points to remember when choosing an EMI/RFI gasket. Evaluat Eng 1997;36(8):6.

[93] O'Shea P. Automated EMI gasketing cuts waste from shielding process. Evaluat Eng 1996;35(8):4.

[94] Anonymous, RFI Shielding Ltd. has the form-in-place gasket solution. Electronic Eng. 1996;68(834):2.

[95] Lee B. Silicone rubber. Engineering 1995;236(10):32–3.

[96] Rothenberg RA, Inman DC, Itani Y. In: IEEE Int. Symp. Electromagnetic Compatibility, Development of commercial grade EMI gaskets, Piscataway, New Jersey, USA: IEEE, 1994, p. 818.

[97] Mottahed BD, Manoochehri S. Investigation of composite materials selection and joint layout design to enhance EMI shielding of electronic equipment. Polym Eng Sci 1997;37(3):653–66.

[98] Shui X, Chung DDL. 0.4 μm diameter nickel filament silicone–matrix resilient composites for electromagnetic interference shielding. J Electron Packag 1997;119(4):236–8.

[99] Jana PB, Mallick AK. Studies on effectiveness of electromagnetic interference shielding in carbon fiber filled polychloroprene composites. J Elastom Plast 1996;31(10):1195–206.

[100] Shui X, Chung DDL. Nickel filament polymer–matrix composites with low surface impedance and high electromagnetic interference shielding effectiveness. J Electron Mater 1997;26(8):928–34.

[101] Chiou J-M, Zheng Q, Chung DDL. Electromagnetic interference shielding by carbon fiber reinforced cement. Composites 1989;20(4):379–81.

[102] Shui X, Chung DDL. Submicron nickel filaments made by electroplating carbon filaments as a new filler material for electromagnetic interference shielding. J Electron Mater 1995;24(2):107–13.

[103] Ramadin Y, Jawad SA, Musameh SM, Ahmad M, Zihlif AM, Paesano A, Martuscelli E, Ragosta G. Electrical and electromagnetic shielding behavior of laminated epoxy–carbon fiber composite. Polym Int 1994;34(2):145–50.

[104] Lin M-S. In: IEEE Int. Symp. Electromagnetic Compatibility, Near-field shielding properties of anisotropic laminated composites, Piscataway, New Jersey, USA: IEEE, 1994, pp. 112–5.

[105] Chiu H-K, Lin M-S, Chen CH. Near-field shielding and reflection characteristics of anisotropic laminated planar composites. IEEE Trans Electromagnetic Compatibility 1997;39(4):332–9.

[106] Roberts JC, Weinhold PD. Design, analysis and fabrication of a graphite/epoxy electronics enclosure flanged aperture, with supporting electromagnetic interference test data. J Compos Mater 1995;29(14):1834–49.

[107] Olivero DA, Radford DW. Integrating EMI shielding into composite structure. SAMPE J 1997;33(1):51–7.

[108] Choate M, Broadbent G. Toughened phenolic SMC for EMI shielding. Thermosets: The True Engineering Polymers, Technical Papers, Regional Tech. Conf. – Soc. Plast. Eng., Brookfield (Connecticut, USA): Society of Plastics Engineers, 1996;69–82.

[109] Wienhold PD, Mehoke DS, Roberts JC, Seylar GR, Kirkbride DL. In: 30th Int. SAMPE Tech. Conf, Electromagnetic interference (EMI) shielding effectiveness, surface resistivity, and RF conductivity of thin composites for spacecraft applications, vol. 30, Covina, California, USA: SAMPE, 1998, pp. 243–55.

[110] Fernyhough A, Yokota Y. Composites are IT. Mater World 1997;5(4):202–4.

[111] Hiramoto T, Terauchi T, Tomibe J. Controlling ESD and absorbing and shielding EMW by using conductive fiber in aircraft. Electrical Overstress/Electrostatic Discharge Symp. Proc., ESD Assoc., Rome (New York, USA): ESD, 1998;18–21.

[112] Morin Jr., LG, Duvall RE. Application for copper and nickel–copper–nickel electroplated carbon fibers for EMI/RFI shielding. Proc. 43rd Int. SAMPE Symp. Exhib., Vol. 43, No. 1. SAMPE, Covina (California, USA): SAMPE, 1998;874–881.

[113] Gaier JR, Terry J. In: 7th Int. SAMPE Electronics Conf, EMI shields made from intercalated graphite composites, vol. 7, Covina, California, USA: SAMPE, 1994, pp. 221–33.

[114] Gaier JR, Davidson ML, Shively RK. In: Technology Transfer in a Global Community, 28th Int. SAMPE Tech. Conf, Durability of intercalated graphite epoxy composites in low Earth orbit, vol. 28, Covina, California, USA: SAMPE, 1996, pp. 1136–47.

[115] Luo X, Chung DDL. Electromagnetic interference shielding reaching 130 dB using flexible graphite. Carbon 1996;34(10):1293–4.