Optimization design of electromagnetic shielding composites

Zhaoming Qu*, Qingguo Wang, Siliang Qin, Xiaofeng Hu
Research Institute of Electrostatic and Electromagnetic Protection, Mechanical Engineering College, Shijiazhuang, Hebei province, China
E-mail: iamqzm@gmail.com

Abstract. The effective electromagnetic parameters physical model of composites and prediction formulas of composites' shielding effectiveness and reflectivity were derived based on micromechanics, variational principle and electromagnetic wave transmission theory. The multi-objective optimization design of multilayer composites was carried out using genetic algorithm. The optimized results indicate that material parameter proportioning of biggest absorption ability can be acquired under the condition of the minimum shielding effectiveness can be satisfied in certain frequency band. The validity of optimization design model was verified and the scheme has certain theoretical value and directive significance to the design of high efficiency shielding composites.

1. Introduction
The prediction of the physical properties (e.g., the dielectric constant, the thermal or electrical conductivity, and the effective elastic constants, etc.) of heterogeneous media has been the subject of scientific and engineering interest spanning more than a century. It has attracted the attention of such luminaries as Maxwell, Rayleigh, and Einstein [1–3]. Many predictive schemes have been well documented. Among these schemes, the Maxwell formula1 for the conductivity of a heterogeneous medium containing a very dilute suspension of spheres is the earliest and most well-known one. Since then, the corresponding formulas for the conductivities of media containing ellipsoids [4] and parallel circular cylinders [5] have been developed. In the current literature, the Maxwell formula for spheres and Fricke’s expressions for ellipsoids are the results of the so-called Maxwell-Garnett effective medium theory [6]. These results hold for very low volume fractions of the dispersed constituents. Recently, Giordano [7] predicted the effective permittivity of two-phase heterogeneous media containing aligned or randomly oriented ellipsoidal inclusions by using the Maxwell formula for ellipsoids and Bruggeman’s scheme.

However, the effective electromagnetic parameters of composite materials for predicting work focused mainly on parameter prediction itself, not with the shielding performance together, made effects of composite microstructure on macroscopical shielding property not intuitive enough. Therefore, the physical model of shielding composite material was proposed and the prediction equation of effective electromagnetic parameters can be obtained based on micromechanics and variational principle, and then using the plane wave transmission theory identifies multilayer shielding effectiveness of materials and reflectivity and equivalent electromagnetic parameters of quantitative relationship and for multilayer composite shielding for multi-objective optimization design.

* To whom any correspondence should be addressed.
Optimization results show that the proposed model is feasible. The scheme proposed here can guide material optimization design, has important theoretical and practical significance.

2. Effective electromagnetic parameters prediction of composite material

Considering a macroscopically homogeneous isotropic material, is filled with ellipsoidal particle filler. Hypothesis of matrix material permittivity is $\varepsilon^1$, the permittivity of filling particles is $\varepsilon^2$. In order to determine the effective permittivity of composite materials, a homogeneous material $\varepsilon^0$ was introduced as reference material. Hypothesis of the existence of the polarization field $\tau$, there are:

$$\tau = \varepsilon^0 \cdot E^0 - \varepsilon^2 \cdot E^2$$  (1)

$$\tau^2 = \varepsilon^2 \cdot E^2 - \varepsilon^0 \cdot E^0$$  (2)

$E^0$ is Electric field intensity outside, $E^2$ is Electric field intensity of filling phase, and $\tau^2$ is polarization field of filling phase. Draw lessons from the mechanics calculation of elastic modulus method [8], in volume $V$ Introduce Green function $G^0$, can be:

$$E^2 = E^0 - \int \left[ G^0(x-x') \cdot \tau - \langle \tau \rangle \right] dV'$$  (3)

$\langle \tau \rangle$ is average of $\tau$ in the volume $V$. By using statistical average method, the polarization field is expressed as:

$$\tau(x) = \lambda^1 \cdot \tau^1 + \lambda^2 \cdot \tau^2$$  (4)

$\lambda^j(x)$ is characteristic function of filling particles, When $x$ in the filling phase is equal to 1, or equal to 0, and the filling phase concentration is $f^j = \langle \lambda^j \rangle$. The ensemble average of formula (3) is:

$$\langle E^2 \rangle = E^0 - \frac{1}{f^2} \sum_{s=1}^{2} A^s \cdot \tau^s$$  (5)

The interaction parameter of micro structure $A^s$ of inter-particle [9] is:

$$A^s = \left\{ \int \lambda^j(\alpha) \lambda^j(\alpha') - f^j \right\} G^0(x-x') dV'$$  (6)

Arranging formula (5) is:

$$E^0 = \frac{\tau^1}{\varepsilon^1 - \varepsilon^0} + \frac{1}{f^2} \sum_{s=1}^{2} A^s \cdot \tau^s$$  (7)

In order to simplify the calculation, we consider only the two-point interaction of material filler particles, ignoring the multi-point effect. Here assuming that the particles in the composite do not lap joint. According to Hashin-Shtrikman [10] variational theory, when the composite filler concentration is not very high, can choose the matrix as a uniform reference material, i.e.:

$$\varepsilon^0 = \varepsilon^1$$  (8)

This can be:

$$A^{21} = f^j \left( \frac{S^2}{\varepsilon^2} - f^j \frac{S^1}{\varepsilon^1} \right)$$  (9)

$S^j$ is particle shape factor, which depends on its structure and size, $S^j$ is particle distribution factor, when the filling phase distributes randomly, $S^j = 1/3$, when the filling phase in the matrix distributes directional, its shape and orientation consistent is same as particles. Finally the Prediction formula can be obtained:
Based on the electromagnetic theory of the principle of reciprocity, the effective permeability of composite material is:

$$\bar{\mu} = \mu_1 + \mu_1 \left\{ \frac{\mu_1}{(\mu_1 - \mu_1)^2} f^2 + \frac{S^2}{f^2} - S^2 \right\}^{1/4}$$  (11)

From the derivation process above-mentioned, in known filler microstructure information (concentration, size, shape and distribution) under the premise, formula (13), (14) can be used in predicting composite equivalent electromagnetic parameters (permittivity and permeability), and then to theoretically predict composite shielding effectiveness and reflectivity.

3. Shielding effectiveness calculation of composites

Figure 1 shows the physical model of composite electromagnetic shielding material, according to the electromagnetic wave theory, when the uniform plane electromagnetic wave vertical incidence the material surface, the input impedance of i layer of material is given:

$$Z_{in}^i = \eta_1 Z_{in}^{i+1} + \eta_i \frac{\tanh(jk, d_i)}{\eta_i + Z_{in}^{i+1} \tan(jk, d_i)}$$  (12)

The characteristic impedance of i layer of material is $\eta_i = \sqrt{\mu_i / \varepsilon_i}$, the Propagation constant of i layer material is $k_i = 2\pi f \sqrt{\mu_i \varepsilon_i}$; $\eta_0 = \sqrt{\mu_0 / \varepsilon_0}$ is vacuum wave impedance, $d_i$ is thickness of i layer material, $\bar{\varepsilon_i}, \bar{\mu_i}$ is equivalent complex permittivity and complex permeability of i layer material, respectively, $c$ is the speed of light in vacuum. When the $n+1$ layer of material is air, $Z_{in}^{n+1} = \eta_{n+1} = \eta_0$, therefore, the reflection coefficient of i layer interface is $R_i = \frac{Z_{in}^i - \eta_{i-1}}{Z_{in}^i + \eta_{i-1}}$, transmission coefficient is $T_i = \frac{2Z_{in}^i}{Z_{in}^i + \eta_{i-1}}$, then the total transmission coefficient of multilayer materials is given:

$$T = \prod_{m=1}^{i+1} T_m \left/ \prod_{m=1}^{i} (e^{-jk_m d_m} + R_m e^{jk_m d_m}) \right.$$

(13)

The shielding effectiveness of multilayer materials is given:

$$\text{Shielding Effectiveness} = -10 \log_{10} T$$
The reflectivity of multilayer materials is given:

$$R = \frac{Z_m^1 - \eta_o}{Z_m^1 + \eta_o}$$  \hspace{1cm} (15)$$

According to the above analysis, the application of multilayer material composite material's shielding effectiveness calculation model can establish the material equivalent electromagnetic parameters and shielding characteristics of the quantitative relationship, the shielding mechanism is more accurate. At the same time, combined with the composite material equivalent electromagnetic parameters prediction models, the procedure of the composite material microstructure to predict the macroscopic equivalent electromagnetic shielding performance design can be realized.

4. Optimization design of shielding composites

Genetic algorithm is a kind of genetics and survival of the fittest mechanism based on global optimization method, it has a robust, efficient features and suitable for processing multiple target optimization design problem of complex system. The relationship of equivalent electromagnetic parameters ($\varepsilon$, $\mu$) of material and filler particle size and concentration is presented above, thus the genetic algorithm can be applied for optimization design the microstructure of composite shielding material, then getting the optimal fill size, concentration and the thickness of each layer, to avoid the blindness of material processing.

The optimizing target set for the given number, maximum thickness, bandwidth and minimum shielding effectiveness under conditions of maximum absorption loss, based on which the layer thickness and the size of the packing and the concentration parameters were optimized. The detail optimization objective is: layers respectively 1, 3 and 5, in determined frequency range $f_{\text{min}} \leq f \leq f_{\text{max}}$, the shielding effectiveness of $SE = F(\gamma, f, d)$ is not less than 70 dB. Requirements: $d = \sum_{i=1}^{5} d_i$ is less than a given maximum thickness of each layer, which $\gamma$ is aspect ratio of fillers, $f$ is concentration of each layers’ filler, and d is given as thickness of each layer material.

Table 1. Optimization result of three layer material.

| layer | thickness | concentration | aspect ratio |
|-------|-----------|---------------|--------------|
| 1     | 0.1 mm    | 24.6 %        | 5.321        |
| 2     | 0.6 mm    | 20.7 %        | 10.48        |
| 3     | 3.3 mm    | 30 %          | 444.4        |

Table 2. Optimization result of five layer material.

| layer | thickness | concentration | aspect ratio |
|-------|-----------|---------------|--------------|
| 1     | 0.25 mm   | 22.97 %       | 11.13        |
| 2     | 0.1 mm    | 23.68 %       | 3.2133       |
| 3     | 0.25 mm   | 23.96 %       | 4.0683       |
| 4     | 0.1 mm    | 27.22 %       | 9.6339       |
| 5     | 3.3 mm    | 30 %          | 444.4        |
According to the above optimization strategy, set the initial population number is 20, the maximum algebra is 500, and mutation rate is 0.01, thickness of shielding material limit below 4 mm. The single layer material optimization results as follows: the thickness is 4 mm, the concentration is 0.3, and the aspect ratio is 444.4. The optimization results of multilayer composite as shown in Table 1 and Table 2.

Table 1 and Table 2 give the optimized results of nickel plated carbon fibre aspect ratio, concentration and thickness of each layer under the condition of shielding effectiveness more than 70dB and the absorption maximum of the materials between the frequency range of 2 ~ 18 GHz. The shielding effectiveness and reflectivity of figure 2 and figure 3 indicate that this paper proposed the multi-objective optimization design method can optimize the electromagnetic shielding material in meet specific shielding characteristics and give optimal material parameters matching, then design and guide the preparation of broadband layer electromagnetic shielding composite materials.

![Comparison of shielding effectiveness.](image1)

**Figure 2.** Comparison of shielding effectiveness.

![Comparison of reflectivity.](image2)

**Figure 3.** Comparison of reflectivity.

5. Conclusions

The effective electromagnetic parameters physical model of composites and prediction formulas of composites’ shielding effectiveness and reflectivity were derived based on micromechanics, variational principle and electromagnetic wave transmission theory. The multi-objective optimization design of multilayer composites was carried out using genetic algorithm. The optimized results indicate that the results show that the proposed optimization method is feasible. The proposed scheme has certain theoretical value and directive significance to design low filler concentration, low cost and high efficiency shielding composites.

References

[1] Maxwell J C *Treatise on Electricity and Magnetism* (Clarendon, Oxford, 1873)
[2] Rayleigh J W 1892 *Philos. Mag.* 34 481
[3] Einstein A 1905 *Ann. Phys.* 19 289
[4] Fricke H 1924 *Phys. Rev.* 24 575
[5] Van Beek L K H, 1967 *Prog. Dielectr.* 7 69
[6] Giordano S 2003 *J. Electrost.* 58 59
[7] Bruggeman D A G 1935 *Ann. Phys.* 24 636
[8] Mura T. *Micromechanics of defects in solids* (Martinus Nijhoff, Dordrecht, 1987)
[9] Ponte P and Willis J R 1995 *J. Mech. Phys. Solids* 43 1919
[10] Hashin Z and Shtrikman S 1963 *J. Mech. Phys. Solids* 11 127