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Modeling emissivity of low-emissivity coating containing horizontally oriented metallic flake particles

Shuai Chen [a], Le Yuan [b], Xiaolong Weng [a,*], Longjiang Deng [a]

[a] National Engineering Research Center of Electromagnetic Radiation Control Materials, University of Electronic Science and Technology of China, Chengdu 610054, PR China
[b] Center for Advanced Materials and Energy, Xihua University, Chengdu, Sichuan 610039, PR China

HIGHLIGHTS

- Emissivity formula of the coating considering binder absorption is established.
- Edge effect of a metallic flake particle to infrared radiation is considered.
- Factors that influence emissivity of the coating are investigated systematically.
- Validity of the model is verified by comparison between experiment and simulation.

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ABSTRACT

The scattering and absorption cross sections of horizontally oriented metallic flake particles are estimated by extended geometric optics that includes diffraction and edge effects. Emissivity of the coating containing those particles is calculated using Kubelka–Munk theory. The dependence of emissivity of the coating on the radius, thickness, content of metallic flake particles and coating thickness is discussed. Finally, theoretical results are compared with the experimental measurements with Al/acrylic resin coating system and the results show that simulation values are in good agreement with experimental ones.

1. Introduction

Low infrared emissivity coatings are widely applied in both military and civil industry, such as in infrared camouflage and low-e glass field [1,2]. These coatings are mainly made of the matrix and functional particles. It is reported that highly infrared transparent binder and highly infrared reflecting particles, such as Al and Cu, facilitate to obtain low infrared emissivity. Once a certain binder is selected, the coating emissivity is mainly affected by the shape, size and orientation of the particles [3,4].

The calculation of emissivity of the coating with spherical particles has received extensive attention because of its relative tractability mathematically [5,6]. Non-spherical particles with random orientation, such as random oriented cylinder and flake particles, are also widely discussed. Appleyard et al. investigated the optical properties of high aspect ratio, highly conducting particles with random orientation by methods FDTD, MoMPC and the equivalent surface area sphere method [7]. Mishchenko et al. discussed the scattering performance of non-spherical dielectric particles with *T*-matrix theory [8]. However, particles that are horizontally oriented in the coating are found experimentally to perform better infrared scattering property than those randomly oriented ones. As far as we know, only very few authors discussed emissivity of these optically anisotropic coatings theoretically. Yuan et al. established a multiple-layer model to calculate emissivity of the coating containing such horizontally oriented metallic flake particles [9]. However, they did not consider diffraction and edge effect of the particles on the infrared radiation in their calculation. According to Chýlek's research, these effects cannot be ignored when the dimensions of the metallic flake particles are in the same order of the wavelengths [10]. So we try to establish a model to calculate emissivity of the coating by taking both effects into consideration.

The arrangement of this paper is as follows: In Section 2, we resolve emissivity formula of the coating system by Kubelka–Munk theory. In Section 3, we calculate parameters in emissivity formula obtained in Section 2. In Section 4, we investigate how various factors influence infrared emissivity of the coating system. Section 5 is the conclusion part.

* Corresponding author. Tel.: +86 15928447491.
E-mail address: csmmqs@163.com (X. Weng).

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2. Kubelka–Munk theory and calculation of emissivity of the coating system

The Kubelka–Munk theory is originally developed by Kubelka and Munk in 1931 [11]. It is assumed that two isotropic diffuse fluxes, the forward flux I and the backward flux J, propagate in opposite directions, as in Fig. 1. These two quantities are coupled by the following differential equations:

$$\frac{dI}{dz} = -(S+K)I + SJ \tag{1}$$

$$\frac{dJ}{dz} = (S+K)J - SI \tag{2}$$

S and K are the effective backscattering and absorption coefficients of the coating system, respectively.

The original model was assumed to calculate the apparent reflectance of particulate coating under diffuse illumination. Saunderson extended the original model to the case of collimated illumination and Saunderson approximation is proved to be valid in cases that involved optically thick films containing weakly absorbing particles [12,13]. The boundary conditions of the differential equations above at the front and back interfaces are:

$$I(0) = (1-r_c)I_e + r_i J_d(0) \tag{3}$$

$$J(d) = R_g I(d) \tag{4}$$

where r_c is the external collimated reflectance at the front interface and r_i is the internal diffuse reflectance at the same location $z = 0$. R_g denotes diffuse reflectance of the substrate. Applying boundary conditions to differential equations, following apparent reflection expression of the coating system results:

$$R_{cd} = r_c + \frac{(1-r_c)(1-r_i)R_{KM}}{1-r_i R_{KM}} \tag{5}$$

where

$$R_{KM} = \frac{1-R_g[a-b\coth(bSd)]}{a+b\coth(bSd)-R_g} \tag{6}$$

and $a = (S+K)/S$, $b = (a^2-1)^{1/2}$.

The emissivity of the coating system is readily available by using Kirchhoff law for opaque substance:

$$\varepsilon = 1 - R_{cd} \tag{7}$$

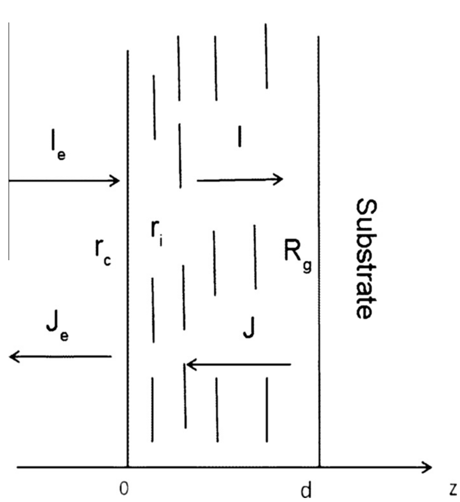

Fig. 1. The schematic diagram of Kubelka–Munk theory.

3. Calculation of the parameters

3.1. Determination of the boundary reflection coefficients

We assume the top surface of the coating layer is optically smooth. In the case of collimated illumination perpendicular to the surface of the coating layer, r_c is obtained easily from the Fresnel relations at the air-coating interface:

$$r_c = \frac{(n_1-1)^2 + k_1^2}{(n_1+1)^2 + k_1^2} \tag{8}$$

where n_1 and k_1 are the real and imaginary part of the complex refractive $N_1 = n_1 + ik_1$ of the binder, respectively.

The internal reflection coefficients r_i for diffuse radiation can be estimated from:

$$r_i = \int_0^{\arcsin(1/n_1)} r(\theta_1)\sin(2\theta_1)d\theta_1 \tag{9}$$

with

$$r(\theta_1) = \frac{1}{2}\left[\frac{\sin^2(\theta_1-\theta_2)}{\sin^2(\theta_1+\theta_2)} + \frac{\tan^2(\theta_1-\theta_2)}{\tan^2(\theta_1+\theta_2)}\right] \tag{10}$$

where θ_1 is the incident angle, θ_2 is the angle of refraction and they are connected by Snell law:

$$n_1 \sin\theta_2 = \sin\theta_1 \tag{11}$$

3.2. Determination of S and K

3.2.1. General expression of S and K

The backscattering coefficient S is given by Emslie et al. [14]:

$$S = N\sigma_{b,sca} \tag{12}$$

where $\sigma_{b,sca}$ is the backscattering cross section of a single particle and N is the number of particles per unit volume.

The effective absorption coefficient K is given in terms of the absorption cross section σ_a of a single particle by

$$K = N\sigma_a + 4\pi(1-f)k_1/\lambda \tag{13}$$

where λ is the wavelength and f is the volume fraction of particles. In the second term of above equation, we take into account absorption of the binder.

3.2.2. Calculation of $\sigma_{b,sca}$ and σ_a of a single flake particle that is perpendicular to the incident light

To simplify the model, we assume that the realistic metallic flake particle is disc-like and its radius and thickness are r and h respectively, as shown in Fig. 2.

Define size parameter x of a disc by

$$x = \frac{2\pi r}{\lambda} \tag{14}$$

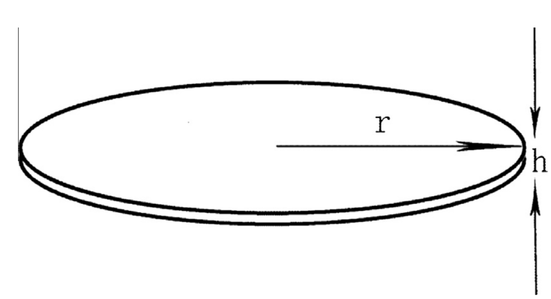

Fig. 2. The schematic diagram of flake particle.