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Experimental evaluation of optimization method for developing ultraviolet barrier coatings

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ABSTRACT

Ultraviolet (UV) barrier coatings can be used to protect many industrial products from UV attack. This study introduces a method of optimizing UV barrier coatings using pigment particles. The radiative properties of the pigment particles were evaluated theoretically, and the optimum particle size was decided from the absorption efficiency and the back-scattering efficiency. UV barrier coatings were prepared with zinc oxide (ZnO) and titanium dioxide (TiO_2). The transmittance of the UV barrier coating was calculated theoretically. The radiative transfer in the UV barrier coating was modeled using the radiation element method by ray emission model (REM^2). In order to validate the calculated results, the transmittances of these coatings were measured by a spectrophotometer. A UV barrier coating with a low UV transmittance and high VIS transmittance could be achieved. The calculated transmittance showed a similar spectral tendency with the measured one. The use of appropriate particles with optimum size, coating thickness and volume fraction will result in effective UV barrier coatings. UV barrier coatings can be achieved by the application of optical engineering.

1. Introduction

Ultraviolet (UV) radiation is a part of the solar spectrum covering the range of 10–380 nm. These wavelengths are invisible to humans, but most people are aware of the effects of UV on the skin, namely, the activation of melanin resulting in a suntan [1]. However, near-ultraviolet is capable of causing long-term skin damage and cancer [2]. An even smaller fraction of ultraviolet is responsible for the formation of vitamin D in all organisms that make this vitamin (including humans) [3]. The UV spectrum thus has many effects, both beneficial and damaging, to human health.

UV light affects industrial products as well. Many polymers used in consumer products are deteriorated by UV light, and therefore require the addition of UV absorbers to protect from UV attack, especially if the products are regularly exposed to sunlight. The problem appears as discoloration or fading, cracking, and, sometimes, total product disintegration if extensive cracking has occurred [4]. The rate of attack increases with exposure time and sunlight intensity. Without changing the appearance of the industrial products, they must be protected from UV light.

Diffey et al. have studied sunscreen protection to protect skin from UV rays [5] while Popov et al. studied the alteration of optical properties of the superficial layer of human skin at UV range by application of nanoparticles of titanium dioxide (TiO_2), silicon (Si) and zinc oxide (ZnO) [6]. Their theoretical study revealed the optimal sizes of the nanoparticles to minimize the light transmittance for UV wavelengths. Shaath introduced a simplified qualitative approach suitable for prediction of the direction of wavelength shifts in the UV absorption spectrum of a sunscreen chemical [7]. For protecting of industrial

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products, Al-Turaif studied the effects of UV radiation on the surface morphology and the surface chemistry of an epoxy-resin-based coating [8]. Cohen et al. studied ultraviolet-barrier coatings producted by polyesters [9]. The coatings have ultraviolet opacity in irradiated film while maintaining visual transparency. Ichinose et al. assessed paint performance over time with respect to surface contamination and degradation of reflectivity by exposure to UV light through environmental exposure tests [4]. Präfke et al. studied vacuum-deposited organic–inorganic hybrid coatings for UV protection of polycarbonate [10]. They carried out UV irradiation experiments to demonstrate the UV protection ability of the hybrid layers. Mainly, these studies were approached from the viewpoint of chemical engineering. In chemical application, it takes a long time to develop such a UV protection coating because it starts from the development of monomers. The development time for applications can be shortened using optical engineering; however, not many studies use these theories. The theoretical optimization using optical engineering in such a UV barrier coating has not been done yet.

This study aimed to realize a UV barrier coating that controls radiation by optimizing the size, volume fraction of particles, and coating thickness. Since the purpose of this paper was to introduce a method of theoretical optimization of UV barrier coatings, a simple coating made of monodispersed spherical pigments in a non-absorbing resin with independent scattering was considered. Additionally, ZnO and TiO_2 were used in the coatings as the pigments. The radiative properties of single pigment particles in a wide range of particle sizes and wavelengths in a non-absorbing resin were calculated based on the Mie theory. Then, the optimal particle sizes were determined from the sum of the back-scattering efficiency $Q_{back,\ sca}$ and the absorption efficiency Q_{abs}. In order to model radiative transfer in a UV barrier coating, radiation analysis using the radiation element method by ray emission model (REM^2) [11] was conducted, and the effects of particle size, optical thickness and particle material on spectral transmittance were discussed. To validate the analytical results, a transmittance measurement was conducted. The coating samples were prepared from the results of the theoretical design. The transmittances of the coating samples were measured in UV and visible (VIS) regions. The experimental results were compared with the results of the numerical analysis.

2. Theoretical design

2.1. Complex refractive index

The scattering and absorption of radiation by a single homogeneous spherical particle in a non-absorbing medium can be obtained by solving the Maxwell equations. The radiative properties of a single spherical particle of diameter, d_p, interacting with an electromagnetic wave of wavelength, λ, are governed by two independent non-dimensional parameters, namely the complex refractive index of the particle $m=n-ik$, and size parameter, $x=\pi d_p/\lambda$ as described in the Mie scattering theory.

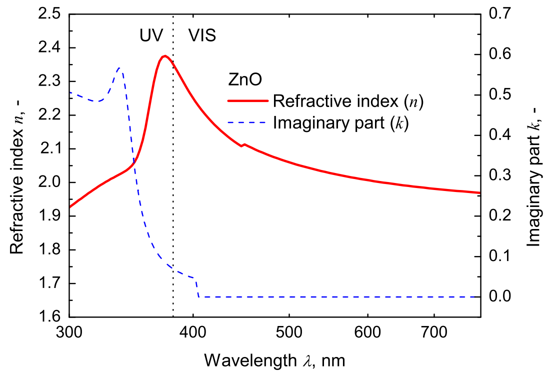

Fig. 1. Complex refractive index $m=n-ik$ of ZnO [12].

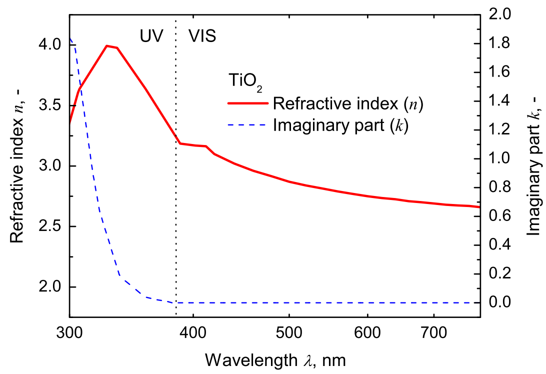

Fig. 2. Complex refractive index $m=n-ik$ of TiO_2 [13].

Figs. 1 and 2 show the spectral distribution of real and imaginary parts of the complex index of refraction of ZnO and TiO_2 in the range of 300–850 nm, respectively [12,13]. As shown in Figs. 1 and 2, the imaginary parts of ZnO and TiO_2 were high in the UV region. In the VIS region, their imaginary parts were zero. From these points, it was considered that these materials were applicable to UV barrier coatings. Using the spectral complex refractive index, the radiative properties of a single particle were calculated [14].

2.2. Radiative properties of single particles

One of the important parameters for optimization of a UV barrier coating is the absorption efficiency factor Q_{abs}. According to the Mie theory, the radiative properties of the particle, such as the phase function, the extinction efficiency factor Q_{ext}, the scattering efficiency factor Q_{sca}, and the absorption efficiency factor Q_{abs}, can be calculated using the following equation [15]:

$$Q_{sca} = \frac{2}{x^2}\sum_{k=1}^{\infty}(2k+1)(|a_n|^2+|b_n|^2), \quad (1)$$

$$Q_{ext} = \frac{2}{x^2}\sum_{k=1}^{\infty}(2k+1)Re[a_n+b_n], \quad (2)$$

$$Q_{abs} = Q_{ext} - Q_{sca}, \quad (3)$$