Optical Reflectance of Metallic Coatings: Effect of Aluminum Flake Orientation

Li-Piin Sung, Maria E. Nadal, Mary E. McKnight, and Egon Marx—National Institute of Standards and Technology*

Brent Laurenti—Eckart America

INTRODUCTION

Metallic coatings are the most popular exterior finishes in the automotive industry and are widely used on other products such as electronics and sporting goods. The changes in lightness with illumination and viewing angles draw attention to the geometric features of these finished products. A metallic finish consists of metallic flakes, typically aluminum (Al) flakes, in a polymer binder, which is often pigmented to create the desired color appearance. Key characteristics that directly affect the optical properties of the metallic coatings are the size, shape, surface roughness, spatial orientation, and concentration of the flakes, and other pigments (additives). This paper will mainly address the effect of flake orientation and, to some extent, flake surface roughness on the distribution of the light scattered by the coating. Flake orientation is strongly dependent upon the surface treatments of the flakes and the processing conditions of the coating application. It is crucial to be able to measure flake orientation accurately and to develop a methodology that can relate flake orientation to the optical properties of the materials and that will provide support for control and prediction of appearance for product design, manufacture, and marketing.

Many efforts have been made to investigate the interrelation between formulation, processing, and spatial distribution of Al flakes in surface coatings and their appearance properties. A few studies have included quantitative measurements of the flake orientation in cured coatings. Usually, flake orientation is determined using microscopy techniques applied to sectioned, cross-cut samples. This approach does not address directly the 3D spatial orientation of the flakes. Recently, Kettler and Richter used combined techniques of goniospectrophotometry, confocal laser scanning microscopy, and microscopy image analysis of cross-cut samples to obtain 3D orientation information. However, it is not obvious how one can deduce optical properties from their orientation data.

A long-standing issue is how to characterize the flake orientation accurately and how to relate orientation information to optical properties. To tackle these problems quantitatively, we have implemented a methodology linking the flake orientation data to the optical properties by integrating measurements and modeling. Our methodology can be described as follows: (1) generation of topographic maps of the flakes in the coating using nondestructive laser scanning confocal microscopy, (2) determination of the 3D spatial orientation distribution of the normals to the flakes from the topographic maps, (3) modeling of the link between flake orientation distribution and optical properties of the coating using a ray scattering model to calculate the optical reflectance, (4) alternatively, modeling of the direct link between topographic maps and optical reflectance to take into account the flake surface roughness, (5) measurement of the angular distribution of the light scattered by the coating, and (6) comparison of measured reflectance values.

A set of aluminum-flake pigmented coatings having different flake orientations was prepared using various spraying conditions. The flake surface topography and the orientations of individual flakes were determined from images obtained by laser scanning confocal microscopy. Reflectance measurements were carried out to quantify the optical properties of the coatings. Both a Gaussian distribution (used to represent the measured flake orientation distribution) and a topographic map (including local surface roughness and orientation) of the flakes were then used as input to a ray scattering model to calculate the optical reflectance of each coating. Flake orientation distributions and examples of measured optical reflectance as a function of scattering angle are shown, and the latter are compared to calculated reflectance values.
and calculated angle-resolved reflectance. The inputs to the ray-scattering models are flake orientation distributions such as Gaussians of varying widths or topographic maps obtained with a confocal microscope. A preliminary report on this work was presented at a meeting. Here, we show results of new measurements, we introduce corrections to some of the formulas, which affect mainly scattering at large angles, and we include a new model that produces a scattering distribution from topographic maps.

EXPERIMENTAL

Materials

Two gray metallic pigmented coating samples were prepared using a conventional hand-held spray gun. Each coating sample consisted of two layers of coating films on a black glass substrate. The first layer, which served as a basecoat, consisted of Al pigments in an acrylic-melamine polymer binder. The second layer was a smooth clearcoat of the same polymer binder as used in the basecoat. The Al pigment was a special automotive grade that has a smooth surface finish and a platelet-like shape. The pigment loading level was 5% by mass fraction based on the solid content of the coating and the average flake size was about 16 μm diameter and 1 μm thickness. We changed the coating appearance using the same composition by varying the amount of fluid allowed to pass through the spray gun. The samples were designated according to the position of the fluid control as 1-turn for normal operation and 1.5-turn for extra fluid output. The final dry film thickness of samples was 38 μm ± 4 μm, measured by a Positector 6000 series coating thickness gauge.

Visually, samples appeared lighter (of greater brightness) near the specular direction and became darker as the viewing angle moved away from this direction. The brightness difference between the two samples was small but visually detectable.

Microstructure Characterization

We used a Zeiss model LSM510 laser scanning confocal microscope (LSCM) to characterize the microstructure of the coatings. The LSCM uses coherent incident light and collects reflected or scattered light exclusively from a single plane, rejecting light out of the focal plane. The wavelength, numerical aperture (N.A.) of the objective, and the size of the collecting pinhole in front of the detector determine the resolution in the axial direction perpendicular to the surface. In this study, an oil immersion objective (100x/1.3) was used. The scanning area of each confocal micrograph was about 92.1 μm x 92.1 μm at 0.18 μm/pixel with a scanning time of 8 sec/frame. The calculated transverse and depth resolutions (point-to-point spread function) for an objective with an N.A. of 1.3 are 155 nm and 286 nm, respectively, for a scanning laser wavelength of 543 nm.

Figure 1a gives an example of a LSCM micrograph of an Al-pigmented coating and the selected image of a single flake. LSCM micrographs consist of images of overlapping optical slices (a stack of z-scan images) with a 0.3-μm frame. The calculated transverse and depth resolutions (point-to-point spread function) for an objective with an N.A. of 1.3 are 155 nm and 286 nm, respectively, for a scanning laser wavelength of 543 nm.

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