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A First Step Towards Photorealistic Rendering of Coated Surfaces and Computer Based Standards of Appearance.

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In an effort to understand the physical basis for coating and surface appearance we are combining the results of optical and surface topographical measurements, mathematical modeling and computer graphic rendering. We seek to explore the feasibility of producing computer graphic images to visualize the color and gloss of surfaces using measured data and models so that rendering becomes a tool to identify important parameters in the material formulation process that contribute to appearance. Here we report on a study of gloss variation in a series of samples with controlled roughness. The work makes use of the sample preparation, characterization and measurement described in [3]. Modeling based on that data was used to produce computer graphic images of the samples. We also briefly describe work on the rendering of data from some early measurements of colored metallic paint.

Goals and General Description of the NIST Appearance Project

As advances in material science and technology have enhanced the ability to manufacture coatings that are exciting and attractive in appearance, customer expectations for these products have increased and with this the challenge of characterizing and predicting appearance at the coatings formulation level. The ability to do this will require a much better understanding of the microstructural basis for coating appearance and the development of tools that can be used to firstly to identify important parameters in the formulation process that contribute to a desired appearance and secondly allow designers to visualize the surface appearance of a proposed formulation as part of a virtual formulation and manufacturing process. The ability to view a virtual end stage product will eventually pave the way to a computer graphics based standard for appearance. This is the vision guiding an ongoing project at the National Institute of Standards and Technology. The project was initiated in response to recommendations by industry [1], and the Council of Optical Radiation Measurements [2] and its purpose is to apply the technical advances in microstructural analysis, optical metrology, mathematical modeling and computer graphic rendering to the development of more accurate methods of modeling and predicting the appearance of coatings and coated objects. The specific research goals are:

- Develop advanced textural, spectral and reflectance metrologies and models for quantifying light scattering from a coating and its constituents and use the resulting measurements to generate scattering maps and validate physical models describing optical scattering from a coating and the relationship that the scattering maps have to the appearance of a coated object

- Integrate measurements and models in making a virtual representation of the appearance of a coating system that can be used as a design tool capable of accurately predicting the appearance properties of coated objects from the optical properties of its constituents.

In this paper we will discuss our progress towards these goals through our investigation of a special case - that of gloss in a black glass sample with a topcoat of clear epoxy. In the course of this discussion we will illustrate the issues involved in achieving them.

Reflectance and Topographical Measurements of Coated Epoxy Samples of Varying Roughness

Sample Preparation

The samples used in this study were made of a clear epoxy coating on a base of black glass. As detailed in [3], the samples had a controlled degree of rms roughness varying from 3 nm to 805 nm . The sample preparation procedure except for the smoothest case began with a mold made of a square steel panel with rms roughness ~1 μm. A new mold with the desired degree of roughness was created from the base mold by a spin coating procedure that applied varying amounts of a surface-modifying polymer to the base material. Roughness decreased as the thickness of the polymer coat increased. The mold was used to create the epoxy sample. See [3] for more details and discussion.

Although the assumption of sample isotropy was not needed in the calculations, the optical reflectance of the sample was compared with measurements of a rotated sample . The differences were not large and this remained true for reflectances obtained from topographical measurements as well.

Optical Scattering and Surface Topographical Measurements

Optical measurements and surface topographical measurements were performed on each of the samples. To understand the nature of the optical measurement it will be helpful to review some definitions. We can assume a ray of light is incident on a sample surface that lies in the x–y plane. If the z-axis is considered to be the normal direction, the direction of the incident ray can be taken to be $(\theta_i, 0)$ where θ_i is the angle between the ray and the z-axis and 0 is the value of the azimuthal angle. If the direction of a scattered ray is defined by the angles (θ_s, ϕ_s), where θ_s is the angle between the ray and the normal direction z and ϕ_s is the azimuthal angle, then the bidirectional distribution function (BRDF) can be defined as:

$$\text{BRDF} = \frac{\text{differential radiance}}{\text{differential irradiance}}$$

Here the irradiance is the light flux (in watts) incident on surface per unit illuminated surface area.The radiance is the light flux scattered through a solid differential angle per unit of illuminated surface area and per unit of projected solid angle [4]. If the solid angle is Ω_s the projected solid angle is $\Omega_s \cos(\theta_s)$. In general terms, the BRDF gives the fraction of incident light reaching a surface from a given direction that is reflected in a specific outgoing direction. Arguments in [4] show that for an isotropic surface we can make the following approximations,

$$\text{BRDF}\ ;\ \frac{dP_s / d\Omega_s}{P_i \cos(\theta_s)}\ ;\ \frac{P_s / \Omega_s}{P_i \cos(\theta_s)}$$

where P_i and P_s are incident and scattered light fluxes. The actual quantity measured by the optical instruments is called the reflectance ρ the ratio of the fluxes, where

$$\rho = P_s \big/ P_i = \mathrm{BRDF} \cdot \Omega_s \cos(\theta_s) .$$

In-plane measurements (i.e. $\phi_i = \phi_s = 0$) were performed on each of the samples and a black glass replica (included for comparison) , using the NIST spectral tri-function automated reference reflectometer (STARR) [3]. Incident light had varying wavelengths in the visible spectrum 500 nm, 550 nm, and 600 nm for incident angles of 20 degrees 45 degrees 60 degrees and 70 degrees and scattering or viewing angles ranged from –75 degrees to 75 degrees in steps of 1 degree. These measurements formed the basis for comparison to computations of the sample reflectance that were based on topographical data i.e. measurements of the surface height that were obtained by interferometric microscopy. See [3] for details of the procedures used.

Light Scattering Calculations and Comparison with Optical Measurements

Calculations of the surface reflectance based on surface topographical measurements were done in two ways. The first uses the Kirchhoff approximation of the solution of the wave equation as developed by P.Beckmann [10]. The second approach- the ray method- is based on the assumption that incident light is specularly reflected by the local tangent plane. The results of reflectance computations using the two methods were compared to measurements carried out with STARR. The agreement, as shown in Figures 1 and 2, for the rough and smooth samples was good, demonstrating the adequacy of the approximations used in the ray method. In addition, its implementation was also computationally efficient enough to generate the large number of incident directions and scattering intensities required to determine a BRDF suitable for a rendering program. We will therefore briefly describe some of its details and follow it with a brief description of the Kirchhoff method.

The Ray Method

A surface topography map of a rectangular patch was obtained using an interferometric microscope. The z or height coordinate was determined for a grid of x- and y-coordinates to represent the sample surface. The local normal to the surface was computed either by fitting a cubic spline to the data or from a tangent plane through an interior point; the method used made little difference for the scattered intensity [3]. The approximate tangent plane was obtained by a least-squares fit of a plane through an interior point by minimizing the sum of the squares of the distances to that plane from the eight nearest neighbors. Once the local unit normal $\hat{n}$ is determined, the wave vector of the incident ray $\vec{k}_i$ can be decomposed into the sum of a component along the local normal and a perpendicular component.

$$\vec{k}_i = \vec{k}_i \cdot \hat{n}\hat{n} + (\vec{k}_i - \vec{k}_i \cdot \hat{n}\hat{n}).$$

The wave vector specularly reflected ray $\vec{k}_s$ is in the plane defined by $\vec{k}_i$ and $\hat{n}$ and it is obtained by simply changing the sign of the component of $\vec{k}_i$ along $\hat{n}$, that is,

$$\vec{k}_s = \vec{k}_i - 2\vec{k}_i \cdot \hat{n}\hat{n}.$$

Therefore the magnitudes of $\vec{k}_i$ and $\vec{k}_s$ are the same, that is, $\vec{k}_s^{\,2} = \vec{k}_i^{\,2}$. Dividing by the common magnitude, we obtain the corresponding relationship between unit vectors,

$$\hat{k}_s = \hat{k}_i - 2\hat{k}_i \cdot \hat{n}\hat{n}.$$

For each direction of incidence, uniform illumination is simulated by computing a reflected ray at each of the interior points. We further assume that a number of detectors are located at various positions to measure the intensity of scattered light. The position of each detector is defined by a

unit vector $\hat{r}_j$ and its aperture by the half-angle α. The angle β between the direction of the *j*th detector and a reflected ray can be determined from

$$\cos\beta = \hat{k}_s \cdot \hat{r}_j .$$

The scattered ray reaches the detector and a "hit" is recorded if $\alpha < \beta$, i.e., if $\cos\beta > \cos\alpha$. The number of detector "hits" is proportional to the radiance (watts/sr) in that scattering direction for the given incident direction. The unnormalized BRDF can be estimated by dividing the computed intensity by $\cos\theta_s$. For the comparison with optical measurements, α was taken to be 1.4 degrees, the half angle of the aperture of the STARR. When this procedure was used for the rendering program, 0.2 degrees was used, based on an estimate of the half angle for a detector representing the human eye.

The Kirchhoff approximation

This approximation of the solution of the scalar wave equation corresponds to a field that is equal to the incident field plus the field reflected by the local tangent plane to the surface in the illuminated region and that vanishes outside this region [3]. A calculation of the phase integral uses the same surface topography map used for the ray approximation, interpolated by a two-dimensional spline function to obtain the surface at about ten points per wavelength. The assumptions used in the Kirchhoff approximation lead to jump discontinuities on the boundary of the illuminated region, which causes the solution to oscillate and vanish like a sinc function for a flat illuminated surface. To avoid the difficulties with discontinuities at the edge of the illuminated region, a windowing function is introduced in the resulting phase integral. We have found that a good windowing is a smooth function that vanishes outside a finite region based on the test function used by Schwartz in his theory of distributions [3].

Computer Graphic Rendering

Rendering is the creation of a synthetic image based on information about the scattering and reflection of light. The specific requirements for rendering a scene are:

- A geometric description of objects in the scene
- The location and strength of light sources in the scene
- A description of how surfaces in the scene reflect incident light- as provided by the BRDF or other angle dependent scattering function.
- The location of a detector or observer's viewpoint.

There are therefore three basic steps in the creation of a computer graphic picture. First the size, shape, and position of the objects in the scene must be defined. Next the light reflection properties of all surfaces must be specified, and the location of the illumination sources in the environment must be given. Finally, a local reflection model is used to determine the color of each surface point, each point is projected onto the picture plane, and the color of the surface location is stored into the appropriate position of the image raster. When each picture element (pixel) has been computed, the image is complete.

The model that is used to characterize light reflection from an object's surface determines the appearance of each object in the scene. There are many parameterized light reflection models that have been developed for use in computer graphic rendering (see e.g. [3]). As shown in Figure 3, most of these models have a general diffuse component and a specular lobe in the mirror direction. The entire reflection distribution is usually a linear combination of the diffuse and

specular portions, and the shape of the diffuse and specular parts is controlled parametrically. These models have been extended to include such effects as anisotropic reflection (Figure 4), polarization, and Fresnel effects.

Allowing for variation with wavelength, the BRDF allows a completely general specification of surface reflection. However, in the context of image synthesis, the use of the BRDF makes it more difficult to compute the color of each point on an object's surface. To achieve a realistic approximation of the reflectance from any differential surface patch, all light impinging on a patch must be gathered. The gathered irradiance is then scaled by the magnitude of the BRDF in the viewing direction (the solid angle leading back to either the eye or the image plane). Of course it would be impossible to sample all incident directions, so a reasonable approximation is achieved by stochastic sampling. A discrete number of rays is cast, each of which is scaled by the magnitude of the BRDF in its particular direction. Then the results are integrated. Increasing the sampling of the BRDF improves the accuracy of the approximation. The technique of stochastically sampling the BRDF is known as Monte Carlo sampling. By reciprocity, one could equally well sample reflecting directions from a surface patch instead of incident directions.

We have developed an efficient method of performing this Monte Carlo integration. Instead of casting rays in a uniform distribution about the hemisphere and weighting the returned value by the reflectance, the ray distribution itself is weighted by the reflectance. This can be done in a straightforward manner when the BRDF is composed of invertible functions such as Gaussians. When the BRDF is represented discretely, either by taking measurements over the hemisphere or by sampling a non-invertible functional form, another method must be used to generate random variates for Monte Carlo integration. This can be accomplished by first subtracting the smallest hemisphere that fits within the BRDF data. This removes the diffuse or uniformly varying portion of the BRDF and leaves only the highly directional specular part. The alias selection method [7] can be employed to create random variates from these remaining specular reflectances.

This Monte Carlo integration scheme has been implemented using the public domain Radiance rendering program [9]. Radiance was designed to facilitate illumination engineering studies and tests have shown that it provides radiometrically correct global lighting simulations. Accurate Radiance surface reflection calculations however, are limited to reflection distributions that can be approximated using the Ward model built into the program [8]. To handle general BRDF data that might only be available as discrete measurements or that may have been approximated using a non-invertible function it was necessary to extend the shading capability of the program. This was accomplished by developing the iBRDF shader that utilizes the efficient Monte Carlo integration technique described in the preceding paragraph.

Computer Graphic Images From Spectral and Reflectance data

To create photorealistic pictures of coated surfaces, a synthetic image must accurately depict both the spectral and spatial distribution of the light reflected from a surface. Therefore, to test the rendering capability of the iBRDF shader, BRDF data with primarily spectral or spatial variation was employed. The spectral data was obtained from a metallic paint and the spatial data from the coated epoxy samples discussed earlier in the paper.

J.G. Davidson made one of the earliest attempts to completely characterize the BRDF of metallic paints. He constructed a spectrogoniophotometer and he used it to make complete in plane reflectance measurements for a sequence of incident light directions. This was repeated for several different metallic paint speciments. Figure 5 was synthesized using the data that Davidson published in his PhD dissertation [5]. To make these pictures, the spectral data in Davidson's tables were reduced to CIE tristimulus values. Then a smoothing interpolation function was fitted and the interpolated data was re-sampled. The Monte Carlo integration

technique described above was then used to turn the re-sampled data into random variates and the image in Figure 5 was created.

To make pictures of the coated epoxy samples a reflectance model based on the Ray method, provided BRDF values that were used to produce the images depicted in Figure 6. The model used surface topographical data from coated epoxy samples with roughness values 201 nm (smooth) and 805 nm (rough) respectively. The model offered enough ease of computation so that sufficient number of BRDF values for incident and outgoing directions were generated. The BRDF data was converted into random variates by the iBRDF shader and then the RADIANCE software was used to perform a Monte Carlo simulation and the image in Figure 6 was created. Thus we have demonstrated a direct link between the material properties of the coated epoxy sample and its predicted appearance.

Conclusions and Future Work

We presented the results of a study of the relationship between surface topography and rendered appearance for an isotropic sample of coated epoxy. Previous work shows good agreement between in-plane optical reflectance measurements and values of the reflectance predicted by a geometric reflectance model. The latter was used in iBRDF, an enhancement of the rendering program RADIANCE and an image was created by a Monte Carlo sampling procedure. Spectral data for metallic paints obtained by J.G. Davidson, was also used in iBRDF to obtain renderings of colored metallic painted objects.

As we turn our attention to more complex materials such as metallic and pearlescent coatings, the challenge will be to develop optical reflectance models that adequately capture their appearance effects and retain enough computational efficiency to be suitable for use in rendering programs. At the same time, we need to gain a better understanding of the role of out of plane measurements and of the optical properties of materials that display subsurface scattering. We can only hope to make partial progress on these difficult issues but the rapid advances in optical metrology, modeling and computer graphics make it likely that the prediction and computer design of coated objects will become a reality in the near future.

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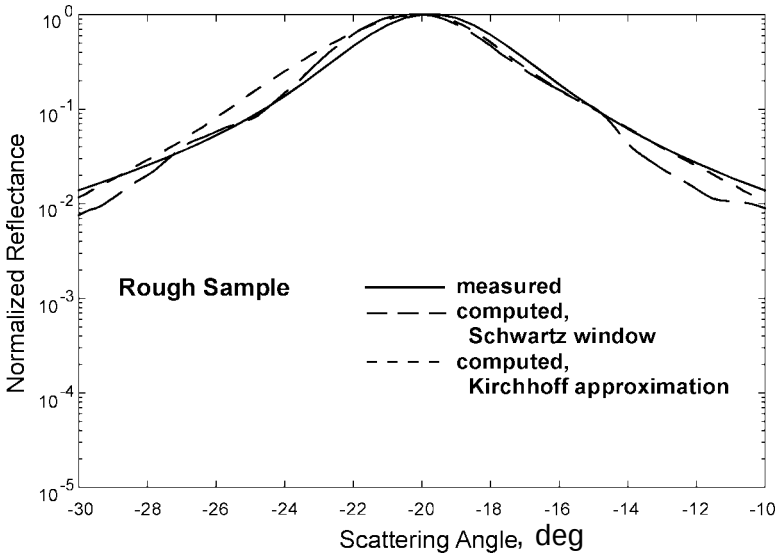

Figure 1. **Comparison of measured and computed intensity distributions for the rough sample**

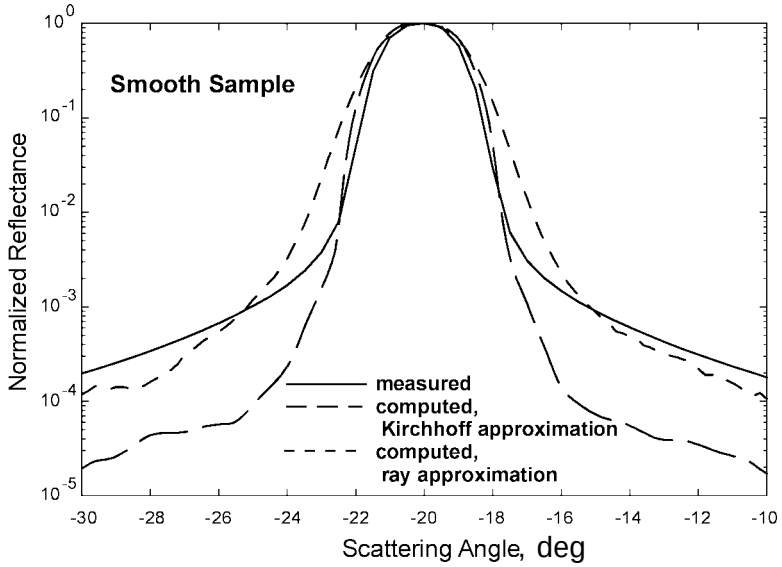

Figure 2. **Comparison of measured and computed intensity distributions for the smooth sample.**

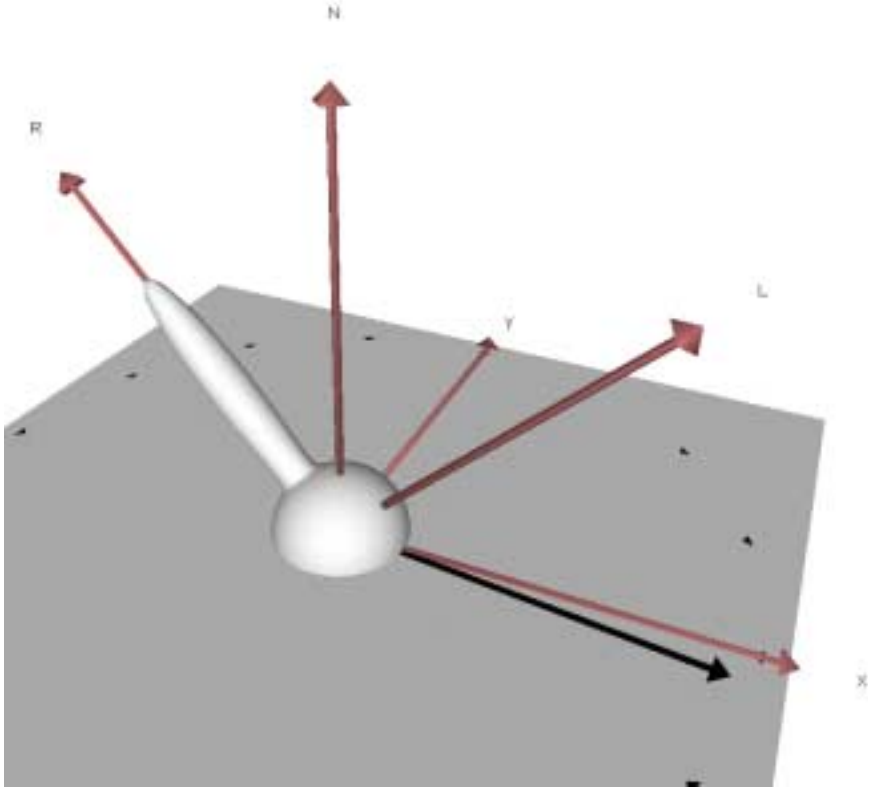

Figure 3- Phong reflection model

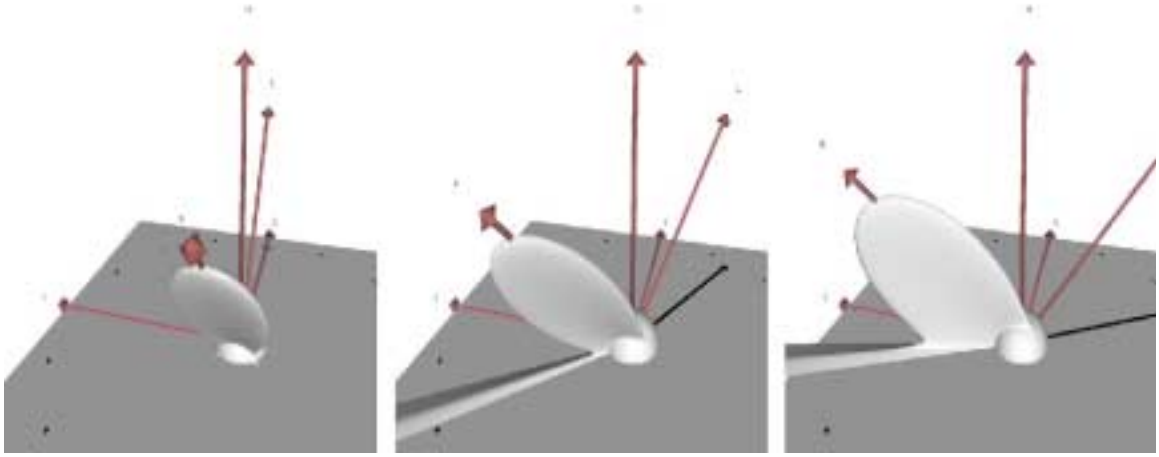

Figure 4. Modeled BRDF illustrating anisotropic reflection (Figure 4), polarization, and Fresnel effects.

Figure 5. **Synthetic image made using iBRDF extension to RADIANCE software and spectrogoniophotometric data from [5].**

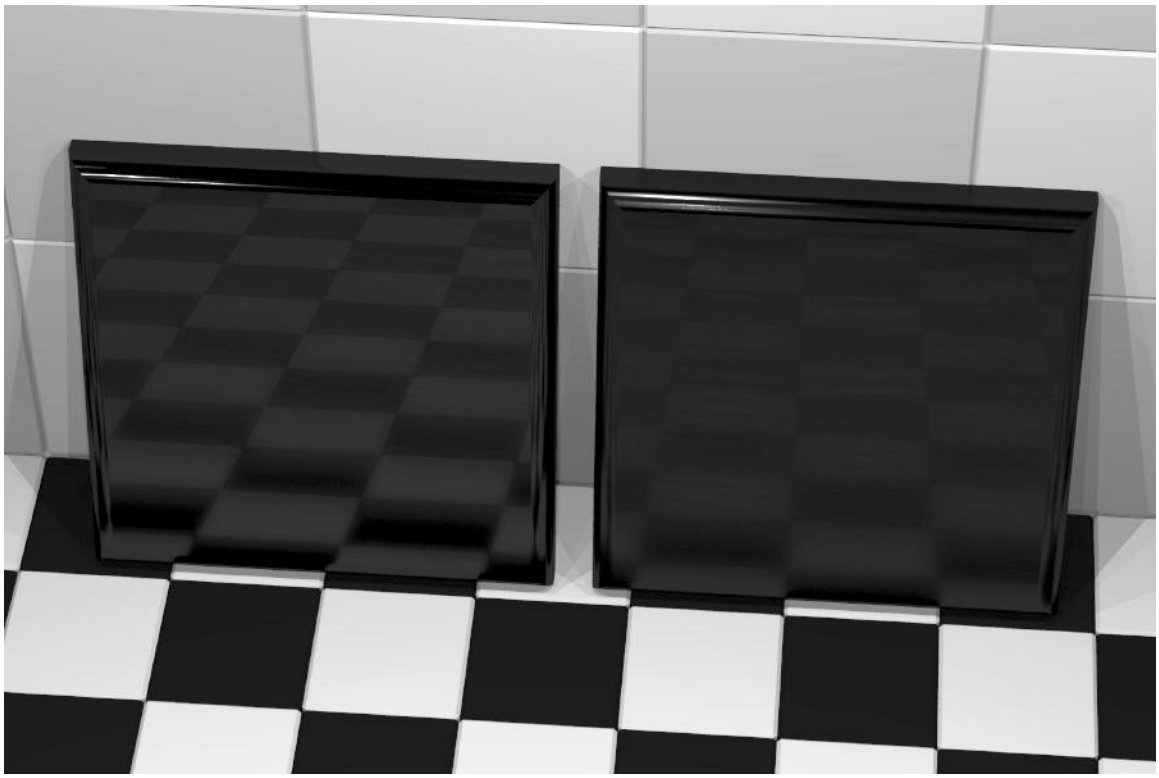

Figure 6. Rendering from reflectance data generated using the Ray method and a surface topographical map of coated epoxy samples with rms roughness values 201 nm (left) and 805 nm (right).