DIFFUSE REFLECTANCE MEASUREMENTS FROM DIFFERENT SURFACES

H. Golnabi*

Institute of Water and Energy, Sharif University of Technology, Tehran, Islamic Republic of Iran

Abstract

Relative diffuse reflection measurements from the original and ground surfaces using a He-Ne laser are reported. The intensity measurements for the metallic, transparent dielectric, matte plastic surfaces and colored papers are presented. Our results indicate that among metallic surfaces tested, aluminum has the highest diffuse reflectance; while the original stainless steel surface shows the lowest. The primary result is that for the ground metallic surfaces, there seems to be an optimum condition and roughness that result in the maximum diffuse reflection. For the color matte plastics, the yellow color has the highest diffuse reflectance and the black one shows the lowest. For the colored papers the yellow paint shows a maximum diffuse reflectance; whereas the gray one has the lowest diffuse reflectance. Our results agree with the theoretical predictions and also with the other experimental results.

Introduction

When a ray of light strikes the surface of an object, it may be absorbed, transmitted, or reflected. Considerable attention has been paid to reflectance study of various surfaces. Some studies have concentrated on the experimental determination of surface reflectance, and at the same time, many theories have been developed for surface reflection modeling [1].

Two limiting cases were considered at the early stages: the light reflected in a particular direction (perfect specular), or the light reflected in all directions of a hemisphere above the surface uniformly (Lambertian). These two ideal cases for a surface are never attained in practice, and it is advisable to consider both effects to describe the reflection properties of a surface.

Keywords: Diffuse reflectance; Metallic surface; Laser; Intensity measurement

The distribution of the reflected light in each case described depends on light direction, wavelength, polarization, and microstructure of the surface layer. For the symmetric surfaces, the reflection is not altered when rotating the surface path about its normal; while in the case of asymmetric surfaces, there is a preferred direction (diffraction in grating). Many surface layers are symmetric and this makes the analysis simple.

In most experiments, light from lamps or laser sources has been used to measure surface properties. Using the laser light in the study of metallic surfaces has been reported by Tanner [2]. Optical methods including specular and diffuse reflection measurements have been introduced. Considering the importance of both specular and diffuse reflectance, in this article we report the relative diffuse reflection measurements from surfaces with different materials, which can provide new information in this respect.

Theory

A reflection theory, which considers the surface radiance as a function of both incident and reflected beams was given by Berthold *et al.* [3]. In that model, a

* *E-mail: golnabi@sina.s.sharif.ac.ir*

function denoted by "f_r" indicates the information about how bright a surface will appear when viewed from a given direction. The bidirectional reflection distribution function (BRDF) defined in that report, shows the ratio of the reflected radiance in direction toward a portion of the surface.

A number of theoretical approaches have been also developed to explain the diffuse reflectance. Different surface profiles have been developed to explain the scattering characteristics of rough surfaces [4,5]. Sinusoidal, sawthooth, rectangular, and random profiles have been used in such studies. There is another model that considers the particle theory in which a powdered sample is treated as a collection of uniformly sized, rough surfaced spherical particles. The effect of roughness on the specular reflection has led to the development of many models. A surface is modeled as a collection of specular V cavities in which the surface normals are assumed to be normally distributed. This is known as Torrance-Sparrow model [6] that is widely used in the computational vision system and graphics.

It has been shown that geometrical optics is applicable when the surface irregularities are much larger than the wavelength of the incident light. Nayar *et al*. [7], reported that in such cases the Torrance-Sparrow model approximates the physical optics model developed by Beckman and Spizzichino [8]. A number of alternative physical-optics approaches to the problem are reported in the literature [9]. All the above models ignore the effect of roughness on the diffuse component of the reflectance, which is the major drawback of both theories.

For surface layers it is possible that light reflected from two different physical paths. Some light is reflected at the interface, and the second reflection occurs when the light crosses the interface. Tominaga and Wandell [10] reported a standard surface reflection model and illuminant estimation for inhomogeneous materials using two independent mechanisms. The result of that study can be used to describe the light reflection from inhomogeneous materials, measured in different viewing geometries, and to estimate the relative spectral power distribution of the ambient light [10].

Scattering from metallic and dielectric rough surfaces is discussed by Saillard and Maystre [11], using the integral theory of metallic and dielectric gratings. Wolff [12] has reported diffuse-reflectance model for smooth dielectric surfaces. Light reflectance from randomly oriented convex particles with rough surfaces has been reported by Shiffer [13]. They considered large particles in comparison with the light wavelength and calculated the differential scattering cross section. In another study, absolute diffuse reflection from relative reflectance measurements has been reported by Lindberg [14].

In this article, we present some of the results given by Ginnken *et al*. [15], which is useful to our discussion. The contribution of the diffuse reflecting part of the radiance is given by

$$L_{rd}(\theta_i,\theta_r,\phi_r,\theta_a,\phi_a) = \frac{\rho}{\pi} E_o \frac{\cos\theta_i^{'}\cos\theta_r^{'}}{(\cos\theta_a)dA\cos\theta_r} \quad (1)$$

where the relative contribution of each point is given by the Lambert's model that is $(\rho/\pi)\cos\theta_i^{'}\cos\theta_r^{'}$. In this model, $E_o\cos\theta_i^{'}$ is the irradiance of the point and ρ shows the Aledo, which can vary between 0 and 1. Here subscript **i** indicates the direction of illumination (xz plane) specified by $\theta_i^{'}$, **r** is the viewing unit vector given by (θ_r,ϕ_r) and **a** is the local surface normal defined by (θ_a,ϕ_r), which is not in general in the z direction. In this geometry because of the surface isotropy, ϕ_r changes from 0 to π. The angles $\theta_i^{'}$, $\theta_r^{'}$ and θ_a are defined in [15]. In Equation (1) factor $(\cos\theta_a)$ considers the project area of each diffusely reflecting part. The total diffuse radiance corrected for masking and shadowing effects is given by integration of Equation (1).

The total radiance according to [15] can be the sum of the specular and diffuse reflections

$$L_r(\theta_i,\theta_r,\phi_r,r,g,c) = C[gL_{rs}(\theta_i,\theta_r,\phi_r,r) + (1-g)L_{rd}(\theta_i,\theta_r,\phi_r,r)] \quad (2)$$

where L_{rs} shows the specular reflection. Parameter r is the measure of the roughness; g indicates the balance between the diffuse and specular reflections, which changes between 0 and 1. The parameter C accounts for proportional to the incident flux, E_o, and overall Albedo, ρ.

Experimental Arrangement

The apparatus used in this study is presented in Figure 1. The light source is a 30-mW He-Ne laser operating at 632.8 nm wavelength. The laser beam is expanded by a 10X telescope and the final beam has a diameter of about 15 mm. A flat aluminum coated mirror directs the collimated beam on the surface under study as shown in Figure 1. In practice, the incident light angle is about 25 degrees and the diffuse reflected beam is blocked by a proper stop.

A collecting lens (f#1.5) is used to focus the scattered light on the photo detector. This lens is placed at a distance of about 10 cm from the test surface. A silicon photodiode (BPX 65 Centronix) is used behind the collecting lens, which converts the diffuse reflected light into the electronic signal. The photodiode is reverse biased to –18 V by using a battery pack and operates in the photoconductive mode. The electric output signal of this detector is connected to a digital voltmeter (1 mV precision) by a coaxial cable.

For optimum detection, a flexible adjusting mechanism is required, so the light detector was mounted on a three-axis transnational stage, which provides a fine and smooth movement of the photodiode in three directions. The photodetector holder was also arranged in such a way that it could be rotate with respect to the incident diffuse light direction. This assembly provides a simple and precise way to collect all the diffused light and to focus it on the small surface area of the detector.

Three groups of samples are prepared for this experiment and each sample could be easily placed in a sample holder. The replacement of the sample for the new one was easily possible in this study. Our samples include: the metallic shims and plates, and papers with the similar dimensions.

For the metallic surface study, we have four different surface finishes defined as unpolished, which is just the original clean surface, a surface ground by the sand paper of mesh grade 400, a surface finish prepared by the sand paper of the mesh grade 800, and finally the surface prepared by the 1200 mesh grade sand paper. In treating the finished metallic surfaces, care must be taken to perform experiment just after the surface preparation. For the second use of such surfaces, those samples were kept in a desicator in order to protect air exposure or some other reaction that may change the surface reflecting quality.

Results and Discussion

To collect data the output signal of the photodetector monitored by the digital voltmeter was measured at least 8 times and average value was recorded for each sample. Because of the small areas of the photodetector and with some other cares, the stray light was negligible and the collected light was purely due to the diffuse reflection. As described, the specular reflection was blocked to prevent leaking into the photodetector, which could cause some errors in measurements.

In metallic surfaces, usually the specular reflection is predominant, so one expects that the diffuse reflectance to be much smaller than specular reflectance. Due to high power of the laser light (30 mW) we were not able to measure the diffuse and specular reflections at the same time in this arrangement. One solution is to use an attenuator for the specular reflection in order to prevent saturation of the photodiode.

In the first experiment, we measured the relative diffuse reflection for some metallic surfaces at the same incident angle and flux. Figure 2 shows the normalized (to Al signal) measured output voltage resulting from different surfaces with the nearly similar surface quality. The results show that among different materials aluminum surface ground with the 1200 mesh grade sand paper has the highest diffuse reflectance (19.2 mV), while the original stainless steel surface has the lowest diffuse reflectance (12.83 mV).

Looking at Figure 2, there seems to be an optimum condition that results in the highest diffuse reflectance. For aluminum, this occurs for the roughest surface ground with the 1200 mesh grade sand paper while for other four surface materials this happens for the surfaces ground with the 800 mesh grade sand paper. At the first look we expected that the highest diffuse reflection would occur for the roughest surface ground with the 400 mesh grade sand paper. As can be seen in Figure 2, this is not the case, and we thought there might be some errors in the experiment. The following experiments showed a similar behavior and this point turned out to be one of the interesting results of this study.

To explain this contradiction that a rougher surface produces less diffuse reflectance, we considered the fact that the diffuse reflection depends on the light characteristics, surface structure, and Albedo, which defines the material reflectivity.

We supposed that the statement “a rougher surface produces more diffused light” must be carefully examined. In this respect in order to change the light distribution on the surface, we took the beam expander and also reduced the light incident angle from 25 to 15 degrees. The result of this experiment for the same surfaces is shown in Figure 3. As expected, in this case, increasing surface roughness caused increase in the diffuse reflectance. Among all surfaces, the original surface shows the lowest diffuse reflection while the ground surfaces with 400 mesh sand paper have the highest diffuse reflections. The difference in the results shown in Figures 2 and 3 can be explained as follows:

Referring to the theory described, it is noticed that the integral probability distribution of the ground and lapped surfaces are different from the original ones and this has been confirmed experimentally [2]. The smoother surface becomes very nonlinear denoting increasing departure from Gaussian in the probability distribution of surface slopes. Therefore, geometrical optics analysis is valid except for the smoothest ground surface. In addition, at some particular roughness value the metallic surface becomes more or less like a mirror type surface with a much higher specular reflection and the minimum diffuse scattering.

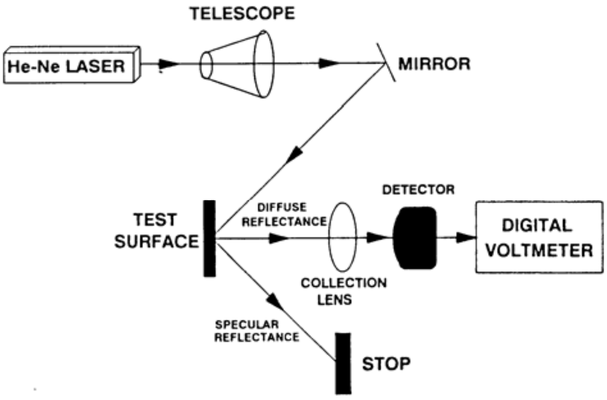

Figure. 1. Block diagram of the apparatus used in this study. It includes a laser light source, a beam expanding telescope, a plane mirror, a collection lens, a stop, a photodetector, and a digital voltmeter.

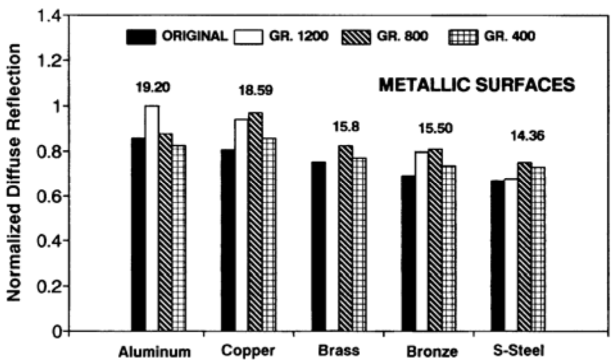

Figure. 2. The relative output signal resulted from diffuse reflection measurements of different metallic surfaces with different surface qualities. The numbers in the graph show the output signals in mV for the input incident power of 30 mW.

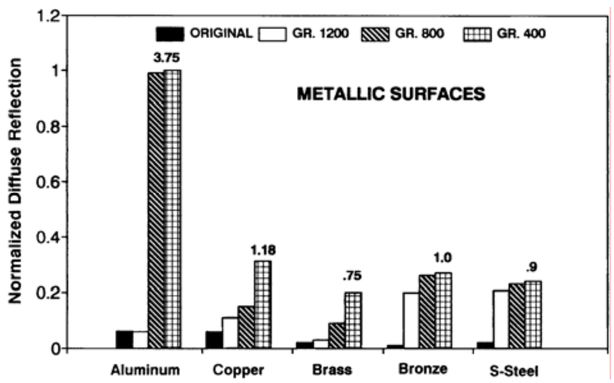

Figure. 3. Normalized diffuse reflection signals measured for the metallic surfaces for the case of no beam expansion. The numbers in the graph show the output signals in mV for the input incident power of 30 mW.

Referring to Equation (2), it is noticed that diffuse reflection depends on the surface distribution function, masking and shadowing effects. Also in Equation (2) for the total diffuse and specular reflections, g shows the balance between these two processes. The reason for difference in the result of Figures 2 and 3 may be the fact that other factors such as, g, can dominate the roughness parameter r, and as a result, the diffuse reflectance is reduced by increasing roughness under some conditions.

When comparing the results of Figures 2 and 3, four points must be considered. First, decreasing the light incident angle results more head on reflections and decreases backscatter light and as a result r has been increased. As can be seen in Figure 3, the measured intensity has been considerably increased in comparison with that of Figure 2. Second when the incident angle is larger (Fig. 2), the probability of the masking and shadowing has been enhanced for the rougher surfaces and as a result we have less diffuse reflection for such surfaces. The third factor is that the field of view of collection lens is about 20 degrees, and for the smaller incident angle more diffused light has been collected by the detection system. The increase of roughness in this case causes that diffused lights scatter at wider angles and less lights fall in this field angle. Finally, the fact that the beam diameter reduction may affect the distribution of light on the surface and also change it from an extended source to a point one. For a higher beam diameter (15 mm), we have diffuse reflection for a more number of local scatter points, which increases the possibility of masking and shadowing contribution. Our impression is that the diffuse reflection increase with the roughness value is not valid for all cases and the surface distribution function and light condition play important roles for each surface analysis.

The role of distribution function has been indicated in [2] for ground and lapped surfaces. The diffuse reflectance for a set of ground surfaces is shown in Figure 8 of that reference. For the smoother surfaces, the curves become very nonlinear, showing increasing departure from Gaussian in the probability distribution of surface slopes. For example for $\sigma = 1.5$ μm (σ is the standard deviation of slopes) this function is linear, but for $\sigma = 0.2$ μm, it becomes nonlinear. In the second study of that report, the effect of lapping after grinding, using a cast iron lapping plate, is reported.

Lapping causes wear off the top of the hills of grinding marks, and forming a flat top but leaving the valleys unchanged. On the other hand, the effect is forming a near-vertical step on the integral probability distribution of roughness height. The result is that with decreasing σ from 1.5 μm to 1.05 μm, the diffuse reflectance shows a decrease while the specular reflectance shows an increase. This comparison is shown in Figure 9 of that report [12].

Comparing our results to that of [2], we believe in that report the range of roughness r has been too small in order to notice such point observed in our experiment. Their diffuse measurement is only for the roughness range of 1.5 μm to 0.2 μm as shown in Figure 8 of that reference. However a careful study of this figure shows that diffuse output varies with the photocell angle square, β^2. In that figure there is a particular angle for each curve that before it, the diffuse reflectivity is lower for higher roughness value. For our case the roughness change due to different mesh grades is expectedly higher and this interesting effect has been enhanced. Another interesting point is that our results back up the effect of parameters given in [15], in which the role of different parameters has been indicated.

The relative diffuse reflectance for transparent dielectric materials such as Kapton and Mylar sheets were examined. Among these materials with different colors, the clear blue sheet has the lowest diffuse reflection (15.75 mV output), while the Mylar sheet shows the highest diffuse reflection (21.81 mV).

In a similar study we considered the similar matte plastic materials with different colors and the results are shown in Figure 4. Here as can be seen in Figure 4, the yellow color matte plastic has the highest diffuse reflectance (26.85 mV); while the black color shows the minimum diffuse reflection (14.39 mV).

In the next study we considered paper materials and the results for thick, thin, and glossy papers are presented in this section. The relative diffuse reflectance for the colored thick papers with a thickness of about 0.5 mm is measured. Among different colors the yellow one has the highest diffuse reflectance (24.52 mV), while the black color shows the least diffuse reflection of about 12.82 mV.

A similar study was accomplished for the thin colored papers and the results are shown in Figure 5. For different colors the yellow one has the highest diffuse reflection (22.28 mV), while gray color has the minimum diffuse reflection (17.68 mV) at this wavelength. The result of diffuse reflection at different light wavelengths is given in Table 11 of [14] for the brown and blue papers. Results of that report indicates that diffuse reflectance for the blue paper at higher wavelengths (900-725 nm) is larger than that of brown paper while for wavelengths ranging 700-600 nm, it is higher for brown paper and again for 275-325 nm, blue paper shows the higher diffuse reflectance. For the wavelength near the laser wavelength (625 nm), brown paper has a diffuse reflectance of 0.44 while blue one has a diffuse reflectance of about 0.37. Our results indicate that diffuse reflectance for brown paper is 18.7 mV, while for the blue paper is 18.56 mV, which is in agreement with the result of [14] for the regular color papers tested in both cases, yellow color shows the highest diffuse reflectance at He-Ne laser wavelength (632.8 nm).

In another study, the diffuse reflectance of the similar glossy papers are measured. The result of this study indicates that glossy white paper has the highest diffuse reflection while the green color shows the minimum diffuse reflection. In order to compare the result of this study with that of regular thin papers (Fig. 5), the results have been normalized to the output of the A4 white paper. For glossy papers, this ratio is 1.07 for red color, 0.5 for green, and 0.81 for brown; while this ratio for regular color papers is 0.64 for red, 0.63 for green, and 0.82 for brown papers.

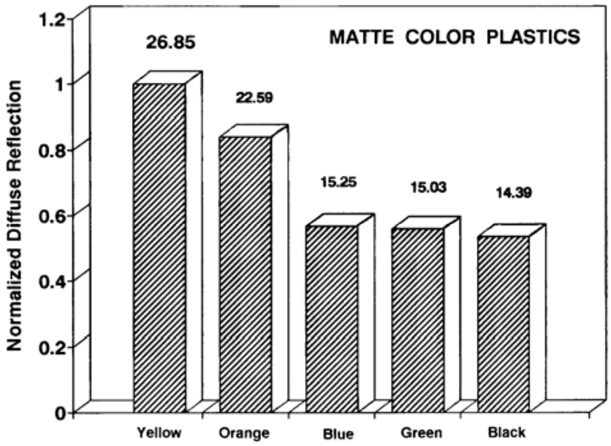

Figure. 4. Normalized diffuse reflection signal measurements for the similar matte plastics with different colors for the input incident power of 30 mW.

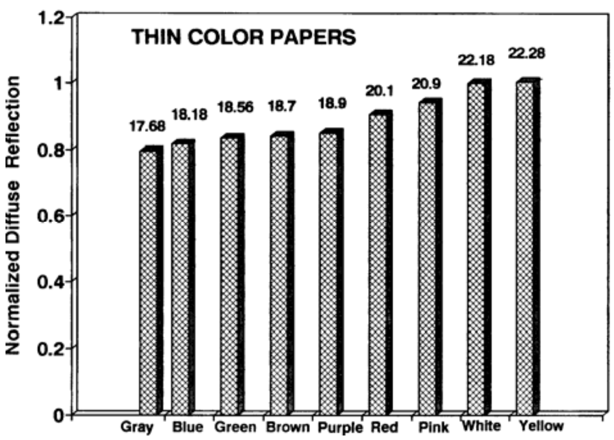

Figure. 5. Normalized diffuse reflection signals for the thin color papers. The numbers in the graph show the output signals in mV for the input incident power of 30 mW.

Finally we have measured the relative diffuse reflectance for some clear dielectric materials. These materials include: a piece of black rubber (2 mm thickness), a piece of printed circuit board dielectric material (1.5 mm thickness), a piece of dark Plexiglas (3 mm thickness), a clear Plexiglas plate (3 mm thick), and white matte plastic (1mm thickness. Among tested materials black rubber shows the lowest diffuse reflectance signal (14.0 mV), while the white plastic material shows the highest diffuse reflectance signal.

In summary, dependence of the reflected light upon the light characteristics and details of the surface structure leads to a complicated problem of interaction of light with surfaces. The mixed reflectance considering both the diffuse and specular reflectance from a surface must be considered in any surface reflection modeling. Experimentally, measurement of both specular and diffuse reflections is required in order to test a model or to describe a surface. This work has provided some results for the relative diffuse reflectance that can be helpful in the field of computer graphics and visual systems, which are based on image formation from scattered light from an object surface. Practically such studies can be used to extract information such as shape or physical properties of surface materials and layers.

Acknowledgements

This work was supported in part by the Sharif University of Technology research program. The author gratefully acknowledges the grant devoted to this research. He is also thankful to A. Asadpour for the performance of the experiments during this study.

References

1. Leader, J. C. *J. Opt. Soc. Am*, **69**: 610-28 (1979).
2. Tanner, L. H. *Optics & Laser Technology*, June, 113-16, (1976).
3. Berthold, K., Horn, P. and Sjoberg, R. W. *Appl. Opt*., **18**: 1770-79 (1979).
4. Lavin, E. P. *Monographs on Applied Optics*, *No 2, Specular Reflection*. Adam Hilger, London, Ch.4 (1971).
5. Stagg, J. and Charalampopulsos, T. T. *Appl. Opt*, **30**: 4113-18 (1991).
6. Torrance, K. and Sparrow, E. *J. of Opt. Soc. Am*, **57**: 1105-14 (1967).
7. Nayar, S. K., Ikeuchi, K. and Kanade, T. *IEEE Trans. Pattern Anal. Mach. Intell.*, **13**: 611-34 (1991).
8. Beckman, P. and Spizzichino, A. *The Scattering of Electromagnetic Waves from Rough Surfaces*. Pergamon Press, New York (1963).
9. Oven, M. and Nayar, S. K. *Int. J. Comput. Vision*, **14**: 227-51 (1995).
10. Tominaga, S. and Wandell, B. A. *J. of Opt. Soc. Am.*, **A7**: 312-17 (1990).
11. Saillard, M. and Maystre, D. *Ibid.*, **A7**: 982-90 (1990).
12. Wolf, L. B. *Ibid.*, **A11**: 2956-68 (1994).
13. Schiffer, R. and Thielheim, K. O. *J. Appl. Phys*, **53**: 2825-31 (1982).
14. Lindberg, J. D. *Appl. Opt.*, **26**: 2900-05 (1987).
15. Ginnken, B. V., Stavridi, M. and Koenderink, J. J. *Ibid.*, **37**: 2900-05 (1998).