Characterization of roughness parameters of metallic surfaces using terahertz reflection spectra

Arunkumar Jagannathan,* Andrew J. Gatesman, and Robert H. Giles

Submillimeter-Wave Technology Laboratory, Department of Physics, University of Massachusetts Lowell, Lowell, Massachusetts 01854, USA

**Corresponding author: arunkumar_jagannathan@student.uml.edu*

Received February 4, 2009; revised April 15, 2009; accepted May 13, 2009; posted May 27, 2009 (Doc. ID 107198); published June 19, 2009

This paper reports on the effect of random Gaussian roughness with rms roughness values of 5–20 μm on the terahertz reflection spectra of metallic aluminum surfaces using Fourier transform IR spectroscopy. By comparing experimental data with a theoretical model based on the Kirchhoff approximation, the rms roughness of a surface is accurately determined. The rms roughness determined by this method is in good agreement with the rms roughness measured using a stylus surface profilometer. In addition, we demonstrate that this method can be used to clearly resolve rough surfaces that differ in rms roughness by approximately 1 μm. © 2009 Optical Society of America

OCIS codes: 290.5880, 300.6495.

A firm understanding of the scattering behavior of terahertz waves from rough surfaces is important to the development of terahertz remote sensing and imaging applications. Electromagnetic waves that are incident on a smooth surface undergo reflection in the specular direction. It is well known, however, that if the surface is even slightly rough, electromagnetic waves are scattered diffusely and result in a loss of intensity in the specular direction [1,2]. The roughness of a surface is primarily characterized by the rms roughness parameter σ. Roughness can be either random or periodic, or a combination of both. The reflectance of a rough surface R_{rough} in the specular direction is given by the Kirchhoff approximation as

$$\mathrm{R}_{\text{rough}} = \mathrm{R}_{\text{smooth}} e^{-(4\pi\sigma k \cos\theta)^2}, \tag{1}$$

where R_{smooth} is the reflectance of a perfectly smooth surface (σ=0), θ is the angle of incidence, and k is the wavenumber [3–7]. The assumptions that are made in deriving Eq. (1) are that (1) the roughness in the surface is random and it is normally distributed; (2) the correlation distance τ of the roughness is much larger than the wavelength of the incident light, i.e., $\tau \gg \lambda$; and (3) there is no multiple scattering between the surface points [1]. The effect of a material's surface roughness on its terahertz reflectance spectra was extensively studied for rough surfaces with σ of 50–160 μm using terahertz time-domain spectroscopy (TDS) [3,4]. The Gaussian roll-off as described by Eq. (1) was also observed for grit papers of various sizes over a frequency range of 0.1–1 THz [5]. As early as 1970, Depew *et al.* used a spectrophotometer in the wavelength range of 0.2 μm–15 μm to determine the rms roughness in aluminum surfaces with σ of 0.1–0.8 μm by analyzing their reflectance spectra [6]. However, to characterize surfaces with rms roughness of several micrometers, the study of terahertz reflectance spectra is required. More recently, the impact of roughness on terahertz reflectance spectra of explosive materials was studied by comparing their reflection spectra with roughened gold samples [7]. Reference [7] further showed that the rms roughness of a single rough gold surface with σ of 9.2 μm can be remotely obtained by using Fourier transform IR (FTIR) spectroscopy. Here, we illustrate that the rms roughness of six different aluminum samples found by fitting FTIR spectra with Eq. (1) had excellent agreement with stylus profilometer data. Moreover, we demonstrate the sensitivity of this method by discerning two nearly identical rough samples whose rms roughness differs by approximately 1 μm. Although previous work has demonstrated a TDS technique for nondestructive evaluation of material degradation, the experiment had difficulties in discerning rough surfaces whose average roughness was below 12 μm [8].

The rough samples used in this experiment were circular with a diameter of 3.7 cm and a thickness of 0.6 cm. The dimensions were chosen in order for the sample to fit in the sample holder of the spectrometer used for collecting the data. The roughness in the samples was created by beadblasting with aggregates of different dimensions. The output pressure of the beadblaster, the distance between the beadblaster nozzle and the sample, and the dimension of the aggregates were the parameters used to achieve the required roughness. Three pairs of samples were created, labeled A, B, and C. The rms roughness of samples A, B, and C were approximately 5 μm, 14 μm, and 17 μm, respectively. Each sample within a pair differed from the other in rms roughness by approximately 1 μm. Sample pairs were created to test the resolvability of the FTIR in discerning two nearly identical samples. The surface profile of the samples was obtained by a Taylor Hobson talysurf profilometer. The histogram of the surface profiles was computed, and the histogram indicated that the roughnesses were approximately normally distributed.

The reflectance measurements were made using a Bruker IFS 66vs FTIR spectrometer. The broadband source was a mercury vapor lamp. A 23-μm-thick My-

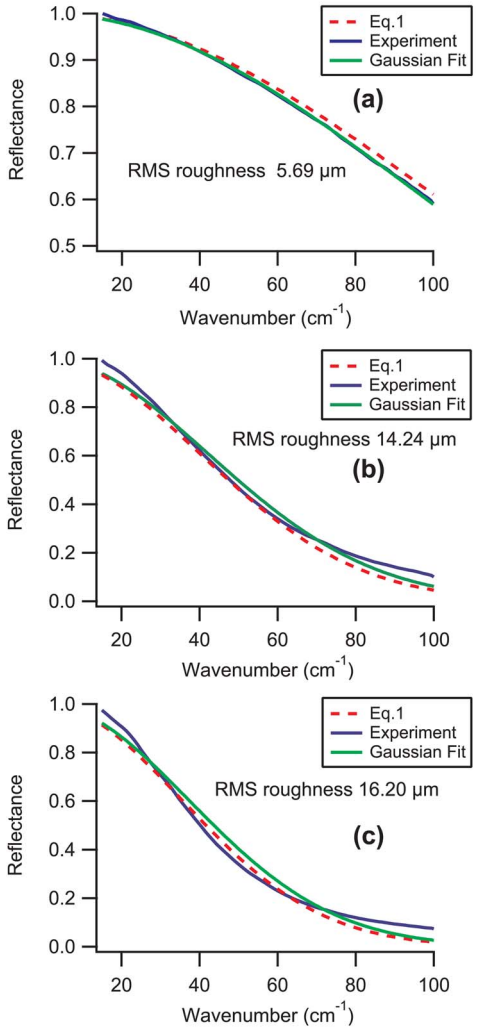

Fig. 1. (Color online) Theoretical, experimental, and Gaussian fit curve for samples (a) A1, (b) B1, and (c) C1.

lar beam splitter was used. A specular reflectance accessory with a fixed angle of incidence of 11 deg was used. A helium cooled silicon bolometer at 4.2 K was used to detect the scattered power in the specular direction. The reference reflector was an aluminum-coated mirror with an assumed 99.5% THz reflectivity [9]. To minimize the impact of systematic fluctuations (power variations in the source, drift in the detector, changes in the amount of water vapor in the beam path, etc.), a background measurement with the reference was taken immediately before each reflectance measurement was taken. The experimental data along with the theoretical curve from Eq. (1) and the Gaussian fit to the experimental data are shown in Fig. 1. From the Gaussian fit in Fig. 1, the fitting coefficient was obtained. The fitting coefficient was compared with Eq. (1), and the rms roughness σ was obtained. The rms roughness obtained from this method for six different samples is shown in Table 1 and had good agreement with the rms roughness obtained using the surface profilometer. Moreover, there is good agreement between theory and experiment throughout the frequency range of 0.3 THz to 3 THz. The experimental curves in Fig. 1 start to deviate from the theoretical curve for wavenumbers less than 20 cm^{-1} and greater than 80 cm^{-1}. This deviation can be attributed to the source instability and the minimal efficiency of the beam splitter at low frequencies and the filter roll-off of the Si bolometer at high frequencies.

The comparison of the terahertz reflectance spectra for samples within a pair are shown in Fig. 2. Here, we illustrate that the FTIR spectroscopy is clearly able to discern two nearly identical samples whose rms difference is less than 1 μm. For all the pairs, the reflectance of the samples in a pair tracks one another over the entire range of frequencies from 0.3 THz to 3 THz. The uncertainty in the reflectance caused by systematic errors in a Bruker FTIR spectrometer is approximately 0.2%. The inset in Fig. 2 shows the comparison of two samples in a pair with error bars for the wavenumber range from 20 cm^{-1} to 30 cm^{1}. From the inset, it is clearly evident that, despite the uncertainties inherent to the system, it was able to resolve the two nearly identical samples. The uncertainty in the rms roughness value calculated from FTIR spectra was approximately 0.4%. Samples in pair A whose rms roughness difference was 0.2 μm were resolvable within the uncertainty limits only for wavenumbers 20 cm^{-1} to 50 cm^{-1} and evaluated with almost identical rms roughness. Hence the difference in rms roughness of 0.2 μm might be the lower limit of resolving rough surfaces using this method, and pair A was specifically chosen to demonstrate this.

In conclusion, we have shown that the rms roughness σ of six different aluminum samples spanning a rms roughness of 5–20 μm was accurately deter-

Table 1. Comparison of rms Roughness Determined from the Surface Profilometer and Using FTIR Data

Sample Name	Roughness from Surface Profilometer (±0.05 μm)	Fitting Coefficient (±0.4% cm)	Roughness Evaluated from FTIR (±0.4% μm)	Percentage Error	RMSE[a] of the fit
A1	5.69	0.007272	5.89	+3.39	0.15
A2	5.50	0.007222	5.85	+6.36	0.16
B1	14.24	0.01672	13.55	−4.84	0.25
B2	13.61	0.01597	12.94	−4.92	0.24
C1	16.20	0.01977	16.02	−1.11	0.22
C2	17.96	0.02218	17.98	+0.11	0.25

[a]rms error.

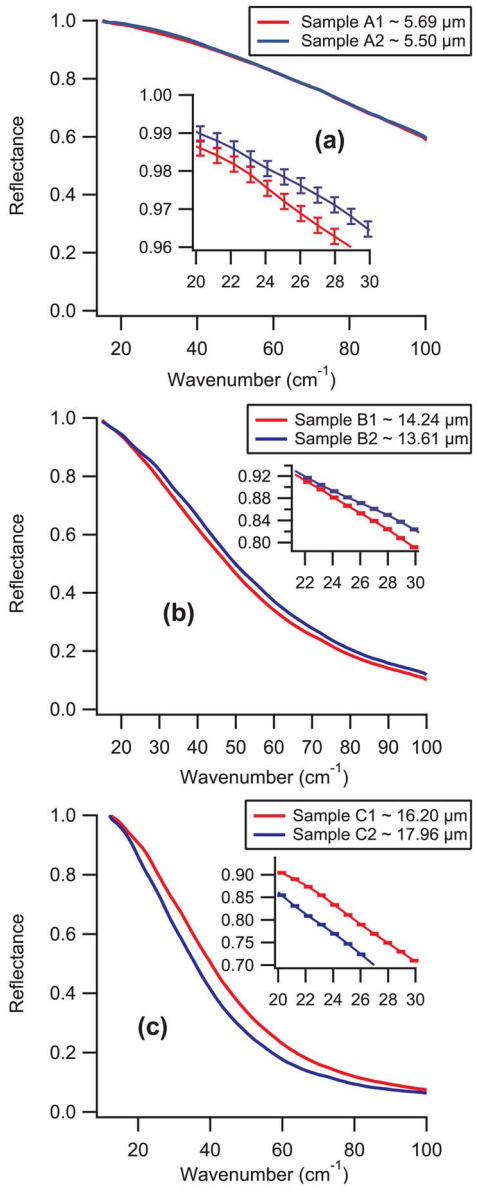

Fig. 2. (Color online) Terahertz reflection spectra of two samples differing in rms roughness by (a) 0.19 μm, (b) 0.63 μm, and (c) 1.76 μm. Inset shown for wavenumbers 20 cm^{-1} to 30 cm^{-1} with error bars.

mined by analyzing terahertz reflectance spectra. The rms roughness obtained by this method had good agreement with the rms roughness σ obtained using a surface profilometer. Moreover, we have illustrated that the terahertz reflectance spectra were able to discern two rough samples that differed in rms roughness by approximately 1 μm. Although real-world applications may not involve metallic surfaces with perfectly normally distributed surface roughness, this Letter simply demonstrates that a terahertz-based nondestructive evaluation system can be used to identify and quantify material degradation in metallic surfaces and the feasibility of using terahertz technology in industrial applications.

This work was supported by U.S. Army National Ground Intelligence Center under contract W911W4-06-C-0020.

References

1. P. Beckmann and A. Spizzichino, *The Scattering of Electromagnetic Waves from Rough Surfaces* (Artech House, 1987), pp. 80–98.
2. S. K Nayar, K. Ikeuchi, and T. Kanade, *IEEE Transactions on Pattern Analysis and Machine Intelligence* (IEEE 1991), pp. 611–634.
3. R. Piesiewicz, C. Jansen, D. Mittleman, T. Kleine-Ostmann, M. Koch, and T. Kürner, *IEEE Transactions on Antennas and Propagation* (IEEE 2007), pp. 3002–3009.
4. Y. Dikmelik and J. B. Spicer, Opt. Lett. **31**, 24, 3653 (2006).
5. Z. Zhou, A. Chen, J. Zhang, L. M. Zurk, B. Orlowski, E. Thorsos, D. Winebrenner, and L. R. Dalton, Proc. SPIE **6772**, 67720T1 (2007).
6. C. A. Depew and R. D. Weir, Appl. Opt. **10**, 969 (1970).
7. M. Ortolani, J. S. Lee, U. Schade, and H.-W. Hübers, Appl. Phys. Lett. **93**, 081906 (2008).
8. R. F. Anastasi and E. I. Madaras, in *Proceedings of the 4th International Workshop on Ultrasonic and Advanced Methods for Nondestructive Testing and Material Characterization* (2006).
9. A. J. Gatesman, R. H. Giles, and J. Waldman, J. Opt. Soc. Am. B **12**, 212 (1995).