Surface Roughness Measurement Using Terahertz Waves

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Abstract

Surface roughness measurement is frequently used in industrial applications, such as assessment of the quality of coatings and paint layers, early detection of corrosion and coating degradation, and characterization of materials. Terahertz (THz) waves, which are electromagnetic waves in the frequency range 100 GHz - 10 THz, can be used for noncontact measurement of the surface roughness of metal or dielectric materials in the order of 10 \( \mu \)m. This range of surface roughness is too large for optical sensors, but too small for microwave sensors. The surface roughness is obtained from the effective reflectivity of the surface, which is the ratio of the spectral intensity of waves reflected from the specimen and from a reference metal plate, whose reflectivity can be assumed to be 1. In this work, the relation between the frequency of THz waves, surface roughness, and effective reflectivity was evaluated by an analytical model and by simulation, and investigated by experiments using sandpaper specimens of varying surface roughness. A broadband THz system using photoconductive antennas for the transmitter and receiver was used in the experiment. Reasonable agreement was obtained between the experimental results and simulation results. The effective reflectivity could be described by a Gaussian function of the surface roughness. The experimental results were compared with measurement results using a contact surface roughness gauge, and were in reasonable agreement. The results showed that THz waves are useful for surface roughness measurement.

Keywords: surface roughness, surface profile, terahertz wave, reflectivity, alumina

1. Introduction

Surface roughness is an important parameter in manufacturing (mainly machining), and various approaches have been made to predict in the machining process(1). In addition, in early stages of corrosion of the substrate metal under a paint layer, small blisters appear on the painted surface, so surface roughness can be used as a parameter to monitor the formation of rust under the paint layer(2).

Conventional surface roughness sensors use a stylus to follow the surface profile, but are inconvenient to cover large surface areas because of its contact nature, and are difficult to apply to vertical or downward-facing surfaces. Noncontact sensors using electromagnetic waves can solve these problems.

Optical techniques such as interferometry, speckle, scattering, diffuseness are used to measure the surface roughness with a resolution in the order of nm(3). However, for surfaces with surface roughness in the order of 10 \( \mu \)m, electromagnetic waves with longer wavelength are more suited. Terahertz (THz) waves are electromagnetic waves in the frequency region between optical waves and radio waves (100 GHz - 10 THz). Since a frequency of 1 THz corresponds to a wavelength of 300 \( \mu \)m, THz waves are sensitive to surface roughness in the order of 10 \( \mu \)m, and can be used for noncontact measurement of the surface roughness\(^{(4,5)}\). Recent progress in THz devices has enabled development of THz sensors which can be used in an industrial environment.

In addition, since THz waves penetrate through paint materials, they can be used to detect corrosion under paint layers\(^{(6)}\). Therefore, surface roughness measurement of the metal substrate, which is hidden under the paint layer, is
also a possibility.

In this paper, the relation between the effective reflectivity of the measured surface and the surface roughness is established based on an analytical model based on the time-of-flight method. Simulations are performed to verify the calculations. Experimental measurement of abrasives with different surface roughness is performed, and the measurement results are compared with those using the conventional method (contact gauge).

2. Model and Simulation

2.1 Analytical Model

The model for scattering from a rough surface is shown in Fig. 1. Here, \( z(x) \) is the surface profile in the normal direction. A plane THz wave with a uniform wavefront is incident in the \( z \)-direction. The reflected wave consists of waves reflected from each point \( x \), for which the time delay relative to an arbitrary reference time is given by \( 2z(x)/c \).

This time delay is simply the round-trip time from the position corresponding to the reference time to the actual surface position.

The electric field of the reflected wave \( E(x) \) from range \( (x, x+dx) \) is given by eq.(1), which shows that the time delay results in a phase difference dependent on the surface profile. Here, \( E_0 \) is the incident amplitude, \( \omega \) is the angular frequency, and \( r \) is the specular reflection coefficient (the specular reflectivity is \( r^2 \)). The electric field of the reflected wave, averaged over all positions \( x \), is given by eq.(2).

\[
E(x,t) = rE_0 e^{-i\omega t \cdot 2z(x)/c} \quad (1)
\]

\[
E(t) = rE_0 e^{-i\omega \left\{ e^{2i\omega z(x)/c} \right\}} \quad (2)
\]

If the surface roughness is zero, \( z(x)=z_0=\text{constant} \), so \( <E(t)> = rE_0 \exp[-i\omega (t-2z_0/c)] \), which shows that the reflected wave is a plane wave with a constant phase factor relative to the incident wave. If the surface roughness is not zero, then the reflected wave will be an ensemble of many waves with different phase factors. This results in interference between the waves which results in the variation of the amplitude of \( E(t) \). The amplitude variation depends on the profile function \( z(x) \).

If the spot size of the incident wave is much larger than the lateral dimension of the surface profile (characteristic length of surface profile variation), then the number of positions which are averaged in eq.(2) is very large. In this case, the surface profile \( z(x) \) can be assumed to follow a normal distribution, with mean \( \mu \) and variance \( \sigma^2 \). In fact, the rms (root-mean-square) value of the surface profile is frequently used to define the surface roughness.

In calculating the ensemble average of the phase factors in eq.(2), the moment function, which is a standard method in statistics(7), is used. For a randomly distributed variable \( X \), the moment generating function is defined as eq.(3), where \(<>\) denotes the expectation value. If \( X \) follows a normal distribution with mean \( \mu \) and variance \( \sigma^2 \), the moment generating function is given by eq.(4).

\[
M_x(r) = \left\{ e^{rx} \right\} \quad (3)
\]

\[
M_x(\tau) = e^{\mu \tau + \frac{1}{2} \tau^2 \sigma^2} \quad (4)
\]

For \( \tau = 1 \), one obtains

\[
\left\{ e^X \right\} = e^{\frac{1}{2} \sigma^2} \quad (5)
\]

Substituting \( X = 2i\omega z/c \) into eq.(5), the ensemble average is given by eq.(6), and \( E(t) \) becomes eq.(7).

\[
\left\{ e^{2i\omega z(x)/c} \right\} = e^{2i\mu c / c - 2i \sigma^2 \sigma^2 / c^2} \quad (6)
\]

\[
E(t) = rE_0 e^{-i\omega (t-2\mu c/c) - 2i \sigma^2 \sigma^2 / c^2} \quad (7)
\]

The effective reflectivity \( R \) is given by the ratio of intensities of the reflected and incident waves, so that

\[
R = \frac{|E(t)|^2}{E_0^2} \quad (8)
\]

\[
R = R_S e^{-4\sigma^2 \sigma^2 / c^2} \quad (9)
\]

where \( R_S = r^2 \) is the specular reflectivity (the reflectivity of a surface with zero roughness). In terms of the frequency \( f \), eq.(9) becomes
\[ R = R_s \exp \left[ -\left( \frac{4\pi f \sigma_z}{c} \right)^2 \right] \]  

(10)

Therefore, the model based on the time-of-flight difference for each point in the \( x \)-direction results in an effective reflectivity which is a Gaussian function of the standard deviation \( \sigma_z \) of the surface profile, which can be treated as the surface roughness.

The result eq.(10) can be understood from the concept of impulse response. For a surface profile which follows a Gaussian distribution in the normal direction, the impulse response (reflection of an extremely short pulse) also follows a Gaussian distribution in the temporal regime. Since any function can be expressed as a summation of impulses, the total response \( E(t) \) will be a superposition of impulse responses, each following a Gaussian distribution. Since the temporal variation of the reflection is directly proportional to the variation in the surface profile, with a proportionality factor of \( \frac{2}{c} \), the spatial variance \( \sigma_z^2 \) of the surface profile will result in a temporal variance \( \sigma_T^2 = \frac{4\sigma_z^2}{c^2} \) in the reflection. For an incident wave of frequency \( f \), the corresponding nondimensional quantity will be \( \omega^2 \sigma_T^2 = \left( \frac{4\pi f \sigma_z}{c} \right)^2 \), which appears in the argument of the exponential function in eq.(10).

2.2 Simulation Using Continuous Wave

Simulations based on the model shown in Fig. 1 were performed. The incident wave is assumed to be a continuous wave with constant frequency \( f \) as in eq.(11). Normal incidence is assumed.

\[ E_i(t) = E_0 e^{-2\pi \beta t} \]  

(11)

A surface profile \( z(x) \) was constructed, for a total of 1000 points in the \( x \)-direction. The variable \( z \) was normally distributed with an average value of 0 and a standard deviation of \( \sigma \). The electric field \( E(x,t) \) for each point was calculated using eq.(1), and numerically averaged over all points (without using the analysis in eq.(3)-(10)). The result \( E(t) \) was substituted into eq.(8) to yield the effective reflectivity. \( R_s \) was set to 1 for simplicity. The process was repeated for different values of \( f \) and \( \sigma \), to obtain the dependence of \( R \) on the frequency and surface roughness.

An example of the simulation result of \( E(t) \), for the cases of \( f=1 \) THz and \( \sigma=0, 20, 40 \) \( \mu m \) is shown in Fig. 2. The calculated results of \( R \) for \( f=0.5, 1.0, 1.5, 2.0 \) THz for the range \( \sigma=0-50 \) \( \mu m \) are shown in Fig. 3 as solid lines. The results were in agreement with the dependence given by eq.(10), shown as broken lines.

2.3 Simulation Using Broadband Wave

The simulation was also performed for a broadband wave generated by a photoconductive antenna. An experimentally measured signal (reflection from a metal plate, using the THz measurement device described in 3.1) was used as the incident wave. The characteristics of the broadband wave are shown in Fig. 4.

The reflected waveform \( E(t) \) was calculated in the same manner as for the continuous wave. In order to compare the results with the case of the continuous wave, reflected waveforms were reconstructed after applying square frequency filters centered at 0.5, 1.0, 1.5, 2.0 THz with widths of 0.2 THz. The simulation result of \( R \) is shown as solid lines in Fig. 5. The broken lines show the dependence based on eq.(10). Since the solid and broken lines are in agreement, the results showed that the width 0.2 THz of the frequency filter was sufficiently narrow so that the reconstructed waveform could be approximated by a continuous wave of the corresponding center frequency.
As shown in Fig. 5, the relation between the effective reflectivity and the surface roughness depends on the center frequency of the frequency filter applied to the broadband wave. Therefore, in order to obtain good sensitivity on the surface roughness, the center frequency should be chosen so that the effective reflectivity variation is large in the region of surface roughness in question. A measure of the sensitivity is the frequency at which the effective reflectivity decreases to 0.5, which is given by eq.(12).

$$f_{1/2} = \frac{\sqrt{\ln 2} \ c}{4\pi \ \sigma_z} = 0.066 \ \frac{c}{\sigma_z}$$  

(12)

The relation between $f_{1/2}$ and the surface roughness is shown in Fig. 6. For example, for $\sigma_z=20 \ \mu m$, the corresponding value is $f_{1/2}=1.0$ THz. Therefore, in order to measure surface roughness around 20 $\mu m$, a frequency filter centered at 1 THz will be appropriate.

3. Experiment

3.1 Procedure

Experiments were carried out to measure the surface roughness of sandpaper specimens. The abrasive used in the sandpaper consists of alumina particles. A THz measurement device (Picometrix, T-Ray 4000), which uses photoconductive antennas for the transmitter and receiver, was used to obtain temporal waveforms of THz waves reflected from sandpaper and Al tape surfaces, the latter used as a reference in calculating the effective reflectivity. The THz wave pulses emitted from the transmitter had a typical time width of 1 ps, and the usable frequency range was 0.1-1.2 THz. The THz wave pulses were focused onto the surface by a polyethylene lens of focal length 25 mm, and the resultant spot size was about 0.6 mm. A schematic diagram of the measurement is shown in Fig. 7.

Since the surface roughness in question is in the order of 10 $\mu m$, the characteristic length of the surface profile in the lateral (in-plane) direction is in the same order. This is much smaller than the spot size, so a large number (in the order of $10^3-10^4$) of local maxima and minima in the surface profile are covered. Therefore, it is safe to assume that the surface profile within the spot follows a normal distribution. In this case, the rms surface roughness is the standard deviation of the surface profile variation.

The refractive index of alumina in the THz region is $n=3.0^{(8)}$. Therefore, the specular reflectivity for normal incidence is $R_s=[(1-n)/(1+n)]^2=0.25$. 

As shown in Fig. 4, the temporal and frequency characteristics of broadband wave generated by a photoconductive antenna.
3.2 Measurement Results

Temporal waveforms \( y(t) \) of THz waves reflected from the sandpaper specimens are shown in Fig. 8(a). The waveform of reflection from Al tape \( y_a(t) \) is also shown. The frequency characteristics are shown in Fig. 8(b).

In obtaining the effective reflectivity \( R \), a square frequency filter with center frequency \( f=1.0 \) THz and width 0.2 THz was applied to \( y(t) \) and \( y_a(t) \), to obtain the filtered waveforms \( y_F(t) \) and \( y_aF(t) \). \( R \) was then calculated from eq.(13), which is the ratio of the maxima of the reflected intensities from the sandpaper specimens and Al tape.

\[
R = \frac{\max[y_F(t)]}{\max[y_aF(t)]} \tag{13}
\]

An example of the filtered waveforms is shown in Fig. 9, for sandpaper specimen #240 and Al tape. The amplitude ratio was \( \max[y_F(t)]/\max[y_aF(t)] = 0.37 \), and the intensity ratio was \( R = 0.13 \). The surface roughness was obtained by substituting this value into eq.(10).

The relation in eq.(10) for \( R_S = 0.25 \) and \( f = 1.0 \) THz is plotted as a solid curve in Fig. 10. The broken lines show the obtained values of \( R \) for each specimen. The surface roughness of each specimen, which is the surface roughness corresponding to the intersections of the solid curve and the dotted lines, is summarized in Table 1. The errors indicate the standard deviation for 3 measurements. In view of eq.(12), \( f_{1/2} = 1.0 \) THz corresponds to \( \sigma_z = 20 \) \( \mu \)m, so the relative accuracy of the values for #240, #180, and #150 is expected to be higher.

<table>
<thead>
<tr>
<th>specimen</th>
<th>( R )</th>
<th>( \sigma_z [\mu \text{m}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>#240</td>
<td>0.134±0.041</td>
<td>19±5</td>
</tr>
<tr>
<td>#180</td>
<td>0.093±0.041</td>
<td>24±5</td>
</tr>
<tr>
<td>#150</td>
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<td>#100</td>
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<td>45±3</td>
</tr>
<tr>
<td>#60</td>
<td>0.013±0.006</td>
<td>42±4</td>
</tr>
</tbody>
</table>

Fig. 7 Schematic diagram of THz wave measurement

Fig. 8 (a) Temporal waveforms and (b) frequency characteristics of THz waves reflected from sandpaper specimens and Al tape

Fig. 9 Example of filtered waveforms (square filter, center frequency 1.0 THz, width 0.2 THz)

Fig. 10 Determination of the surface roughness (solid curve: analytical model, broken lines: measured results)
3.3 Verification

The rms surface roughness of the sandpaper specimens was measured using a contact surface roughness gauge (Mitsutoyo, SurfTest SJ-201). The measurement was performed for 3 positions on each specimen. Comparison of the THz wave and surface roughness gauge measurement results is shown in Fig. 11. Reasonable agreement (within the range of measurement error) was obtained for specimens #240, #180, and #150. For specimens #100 and #60, the values obtained by THz measurement were significantly larger than those obtained by the roughness gauge. A possible cause of this discrepancy is the fact that the center frequency of the frequency filter (1 THz) did not match $f_{1/2}$, which is 0.5 THz for $\sigma_z=40$ $\mu$m.

The surface roughness values obtained by THz waves were consistently higher than those measured by the surface roughness gauge, suggesting the presence of a systematic error. A possible cause is the effect of the paint layer which coats the abrasive. In Fig. 8(b), dips in the frequency spectra are seen, which result from the étalon effect of the thin paint layer. These may have resulted in lower effective reflectivity and higher surface roughness values.

4. Conclusion

Surface roughness measurement using THz waves was investigated. An analytical model using the time-of-flight method and simulation showed that the effective reflectivity of the surface followed a Gaussian function of the surface roughness. The surface roughness of sandpaper specimens measured by a THz measurement device were in reasonable agreement with the rms surface roughness measured by a contact roughness gauge, for surface roughness 15-25 $\mu$m.

Development of methods to eliminate the effect of the paint layer, optimization of frequency filtering of the broadband wave, waveform analysis methods are of further study. Applications such as surface roughness measurement of plasma-sprayed coatings can be expected in the near future.

References

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