Published in final edited form as:

Ultrasonics. 2009 January ; 49(1): 10–14. doi:10.1016/j.ultras.2008.06.011.

Continuous-wave ultrasound reflectometry for surface roughness imaging applications

F. G. Mitri, R. R. Kinnick, J. F. Greenleaf, and M. Fatemi

Mayo Clinic, College of Medicine, Department of Physiology and Biomedical Engineering,
Ultrasound Research Laboratory, 200 First Street SW, Rochester MN 55905, United States.
mitri@ieee.org, mitri.farid@mayo.edu

Abstract

Background—Measurement of surface roughness irregularities that result from various sources such as manufacturing processes, surface damage, and corrosion, is an important indicator of product quality for many nondestructive testing (NDT) industries. Many techniques exist, however because of their qualitative, time-consuming and direct-contact modes, it is of some importance to work out new experimental methods and efficient tools for quantitative estimation of surface roughness.

Objective and Method—Here we present continuous-wave ultrasound reflectometry (CWUR) as a novel nondestructive modality for imaging and measuring surface roughness in a non-contact mode. In CWUR, voltage variations due to phase shifts in the reflected ultrasound waves are recorded and processed to form an image of surface roughness.

Results—An acrylic test block with surface irregularities ranging from 4.22 μm to 19.05 μm as measured by a coordinate measuring machine (CMM), is scanned by an ultrasound transducer having a diameter of 45 mm, a focal distance of 70 mm, and a central frequency of 3 MHz. It is shown that CWUR technique gives very good agreement with the results obtained through CMM inasmuch as the maximum average percent error is around 11.5%.

Conclusion—Images obtained here demonstrate that CWUR may be used as a powerful noncontact and quantitative tool for nondestructive inspection and imaging of surface irregularities at the micron-size level with an average error of less than 11.5%.

Keywords

Continuous Wave; Ultrasound; Reflectometry; Surface roughness imaging; Phase; Nondestructive imaging

Measurement of surface roughness irregularities that result from various sources such as manufacturing processes, surface damage, and corrosion, is an important indicator of product quality for many nondestructive testing (NDT) industries. Components and structures dimensioned from microns to centimeters can be found in semiconductors, data storage, microstructures and sensors, but also in precision manufacturing and engineering for automotive and aerospace industries. In industrial manufacturing, compliance with given tolerances needs to be checked as often as possible so that faulty parts are eliminated before

Correspondence to: F. G. Mitri.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

any further processing steps are taken thereby avoiding additional manufacturing costs on an already defective part. For example, in semiconductor manufacturing, roughness of bare silicon wafers is measured after polishing and cleaning. Excessive roughness destroys the integrity of very thin layers [1]. Roughness measurement is equally important for other semiconductors and materials such as ceramics, glasses, papers, and polymers.

In common manufacturing applications, contact measurement processes can make surface roughness measurements but take a long time (in the order of minutes to an hour), making them incompatible with the instantaneous feedback needed for high throughput production control. In addition, because of the contact, there is the risk of damage to the surface of the item being tested. These observations have provided the impetus for many investigators to seek a variety of imaging technologies [2–18] for the inspection and measurement of surface roughness. The ultimate goal in this line of research is to quantitatively evaluate the roughness of a surface. However, many of today's ultrasound NDT methods provide a relative or qualitative measure/image of surface roughness. This should not undermine the development of novel imaging tools, because in most imaging modalities, even a qualitative image with good contrast and resolution can be very useful for the inspection and detection of micro-cracks, delaminations or flaws. Optical techniques are the most popular non-contact techniques. They are generally insensitive to the material property of the surface, but sensitive to the property of the transmitting medium. However, most optical methods are still limited to the laboratory implementation due to the difficulty of adapting them to harsh manufacturing environments as well as the cost of constructing such systems. On the other hand, ultrasonic techniques have been suggested for noncontact measurement and inspection of surface roughness [5].

Here, we introduce continuous-wave ultrasound reflectometry (CWUR) as a quantitative technique for the determination of micron-size surface roughness. This novel nondestructive imaging tool uses one single transducer driven with *continuous-wave* ultrasound, focused at a point on the surface to be imaged. The reflected/backscattered ultrasound waves reach the concave surface of the transducer and therefore modulate the input voltage fed to the transducer. Surface roughness variations induce phase changes in the reflected ultrasound signals, which in turn, cause amplitude changes in the input voltage when the reflected waves reach the surface of the transducer. To form a roughness image of the surface of an object, these phase shift-based voltage variations are recorded and processed.

A test block made of acrylic material is constructed for the experiment. This block is designed in such a way that one side has four steps, a flat area in its middle part, and a ramp with an angle of inclination on the other side. The rear side of the block is shaped as two sloping surfaces to deflect the ultrasound beam and prevent possible reverberation (see Fig. 1). To calibrate the acrylic block, a step height measurement was performed using a Brown & Sharpe coordinate measuring machine (CMM), Model Global 575 by Domaille Engineering LLC. On contact with the CMM, a height-sensitive probe is directly connected to the surface of the block and measures roughness variations and inclination. The calibration height measurements are shown in Fig. 1.

A schematic of the experimental setup for the CWUR technique is shown in Fig. 2. In this technique, an ultrasound beam is generated by a single-element spherically focused transducer. The transducer has a diameter of 45 mm, a focal distance denoted by $z_0 = 70$ mm and operates at a central frequency of 3 MHz. The element is driven by a continuous wave (CW) signal obtained from a function generator (Model 33120A, Agilent Corp.), through a current amplifier (LH0063, National Semiconductor Corp.). The block rests on an acrylic plate, secured by two rubber bands to avoid sliding. The whole system (block + plate) is mounted on a three-axis positioning system and immersed in a tank of degassed water. The test block surface is placed in the focal plane of the transducer. The transmitted voltage signal and the transducer voltage

signal (containing both the transmitted voltage signal and the voltage variations induced by reflected waves) are isolated with buffer amplifiers (LH0033, National Semiconductor Corp.) and then subtracted using a differential amplifier (LT1364, Linear Technology Corp.) (Fig. 2). Since the voltage variations induced on the transducer signal are small compared to the transmitted voltage, it is necessary to phase shift the transmitted signal before the differential amplifier to bring the two signals into phase, to effect a nearly complete subtraction at the starting point of a scan, thereby increasing the sensitivity of the final signal. The value of the required phase shift depends on both the water path delay between the transducer and object and the accumulated phase shifts through the various electronics. The subtracted signal then represents only the amplified voltage variations due to changes in the surface topography. The output of the differential amplifier is digitized by a 12 bits/sample digitizer (HP E1429A, Hewlett Packard, Inc.) at a rate sufficiently higher than the Nyquist rate. The data are then converted to intensity values for display as an image on a computer.

The underlying mechanism for the CWUR imaging modality is based on simple physics of wave propagation and reflection. The general expression for the continuous-wave acoustic pressure *received* at the surface of the transducer is represented by

$$P_{transducer} = \Re \left\{ A e^{i\omega t} + \sum_{n=1}^{\infty} (AB)^n e^{i(\omega t + (2n-1)\omega z/c)} \right\}, \quad (1)$$

where $\Re$ denotes the real part of a complex number, A is the amplitude of the incident pressure wave, B is the reflection coefficient of the object under test, ω is the angular frequency, c is the speed of sound in the medium of wave propagation, z is the axial distance that equals z_0 at the focal plane, and the integer n accounts for the multiple back-and-forth reflections between the object and the concave surface of the transducer. The reflection coefficient for the acrylic block was measured by conventional pulse-echo ultrasound using the amplitude ratio of the second to first reflected ultrasound pulses. The reflection coefficient is found to be $B \approx 0.15$. For such a material, the ratio of the first to second-order reflection is on the order of $1/B \approx 6.7$. Therefore, we may limit this analysis to the first-order reflection and re-express the pressure received at the surface of the transducer by

$$P_{transducer} = \Re \left\{ A e^{i\omega t} + A B e^{i(\omega t + \Phi)} \right\}, \quad (2)$$

where $\Phi = 4\pi z/\lambda$, and λ is the ultrasound wavelength in the medium of wave propagation.

The experimental method to determine the roughness variation for which CWUR can be applied, is based on detecting the changes in the voltage due to the phase variations related to the parameter z . Detecting voltage variations requires isolating the term containing the phase shift. The procedure is to use a differential amplifier (Fig. 2) to eliminate the voltage induced by the incident wave. The ultrasound frequency is set at 3 MHz. The test block is positioned normal to the ultrasound beam such that it is focused at the flat surface of the block. An area of $12 \times 80 \text{ mm}^2$ is scanned in increments of 0.25 mm in either direction and the voltage variations are recorded. The resulting CWUR image is shown in the middle panel of Fig. 3. Figure 4 shows a one-line profile along the center of the image. From this figure, one notices that small surface variations are well identified in addition to the ramp on the right hand side of the block. One notices however a large difference in the relative amplitude between each of the steps (left side), even though the step heights vary from 14.22 to 19.05 μm as measured by the CMM. This is explained by the fact that the pressure amplitude signal obeys a trigonometric

(nonlinear) relation versus distance (roughness) or phase. Assuming that $A = 1$, and using the sum-to-product trigonometric formulas, Eq. (2) can be rewritten as

$$P_{transducer} = \cos(\omega t) + B \cos(\omega t + \Phi),$$

$$= \sqrt{[1 + B \cos(\Phi)]^2 + [B \sin(\Phi)]^2} \cos\left(\omega t + \tan^{-1}\left(\frac{B \sin(\Phi)}{1 + B \cos(\Phi)}\right)\right). \quad (3)$$

Eq. (3) is of the form

$$P_{transducer} = \Lambda \cos(\omega t + \Theta), \quad (4)$$

$$\text{where } \Lambda = \sqrt{[1 + B \cos(\Phi)]^2 + [B \sin(\Phi)]^2}, \text{ and } \Theta = \tan^{-1}\left(\frac{B \sin(\Phi)}{1 + B \cos(\Phi)}\right).$$

The signal amplitude $\hat{S}$ is directly related to Λ , which in turn, is related to the variations in the axial direction such that

$$\hat{S} = \Lambda = \sqrt{[1 + B \cos(4\pi(z - z_0)/\lambda)]^2 + [B \sin(4\pi(z - z_0)/\lambda)]^2}. \quad (5)$$

Surface roughness requires determining the relative roughness $z - z_0$ from Eq. (5) such that

$$z - z_0 = \left| \frac{\lambda}{4\pi} \tan^{-1} \left(\frac{\sqrt{2B^2 - 1 + 2\hat{S}^2} - B^4 + 2B^2\hat{S}^2 - \hat{S}^4}{1 + B^2 - \hat{S}^2} \right) \right|. \quad (6)$$

For this transducer, the ultrasound wavelength in water is $\lambda = 0.5$ mm.

After processing the relative amplitude of the signal $\hat{S}$ shown in Fig. 4 through Eq. (6), *relative* surface roughness variations (i.e. $z - z_0$) are obtained and displayed in Fig. 5. The surface heights are therefore obtained by calculating the difference between the two points at the edge of each step. As shown in this figure, small surface roughness variations are identified in a *quantitative* manner. To further assess the ability of CWUR in measuring surface roughness, height measurements and inclination values obtained through the CMM and CWUR methods are listed and compared in Table 1. As it is observed from these values, the CWUR technique gives good agreement with the results obtained through CMM inasmuch as the maximum average percent error is around 11.5%. Therefore, the CWUR technique is well adapted for quantitative nondestructive measurement of surface roughness in an efficient non-contact mode.

In conclusion, the CWUR technique is introduced as a novel nondestructive modality for quantitative imaging and measurement of surface roughness in a non-contact mode. Voltage variations due to phase shifts in the reflected ultrasound waves are recorded and processed to form an image of surface irregularities ranging from 4.22 μm to 19.05 μm . It is shown that CWUR technique gives very good agreement with the results obtained through a coordinate measuring machine (CMM) inasmuch as the maximum average percent error is around 11.5%. Increased sensitivity of the CWUR technique can be obtained by using a higher center frequency ultrasound transducer. The experiments presented here were conducted in water.

However, airborne CWUR could also be performed using air-coupled transducers. The results of this study may have implications in other CWUR applications. CWUR may be used for imaging the distribution of the ultrasound reflection coefficient. However, it is anticipated that the surface roughness image may be affected if the object to be imaged has variable reflection coefficient or vice versa. Therefore the resulting image would be a compounded image of surface roughness and ultrasound reflection distribution.

Acknowledgments

The first author acknowledges U. Eberlein for her help in performing the experiments. This work is supported by grant EB 00535-04 from the National Institute of Health.

References

1. Chang CC, Wu XD, Ramesh R, Xi XX, Ravi TS, Venkatesan T, Hwang DM, Muenchausen RE, Foltyn S, Nogar NS. Origin of surface roughness for c-axis oriented Y-Ba-Cu-O superconducting films. *Applied Physics Letters* 1990;57:1814–1816.
2. Lemons RA, Quate CF. Acoustic microscope---scanning version. *Applied Physics Letters* 1974;24:163–165.
3. Honda K, Ohsawa A, Toyokura N. Silicon surface roughness---Structural observation by reflection electron microscopy. *Applied Physics Letters* 1986;48:779–781.
4. Robach Y, Phaner M, Villeneuve Cd, Porte L. Evaluation of surface roughness of technological InP substrates by in situ scanning tunneling microscopy imaging in H₂SO₄ solution. *Applied Physics Letters* 1992;61:2551–2553.
5. Blessing GV, Slotwinski JA, Eitzen DG, Ryan HM. Ultrasonic measurements of surface roughness. *Appl Optics* 1993;32:3433–3437.
6. Yu Z, Boseck S. Scanning acoustic microscopy and its applications to material characterization. *Reviews of Modern Physics* 1995;67:863–891.
7. Teichert C, MacKay JF, Savage DE, Lagally MG, Brohl M, Wagner P. Comparison of surface roughness of polished silicon wafers measured by light scattering topography, soft-x-ray scattering, and atomic-force microscopy. *Applied Physics Letters* 1995;66:2346–2348.
8. Fang SJ, Chen W, Yamanaka T, Helms CR. Comparison of Si surface roughness measured by atomic force microscopy and ellipsometry. *Applied Physics Letters* 1996;68:2837–2839.
9. Briers R, Leroy O, Devolder S, Wevers M, De Meester P. Surface roughness determination using the acousto-optic technique: Theory and experiment. *Applied Physics Letters* 1997;71:599–601.
10. Akkerman ZL, Song Y, Yin Z, Smith FW, Gat R. In situ determination of the surface roughness of diamond films using optical pyrometry. *Applied Physics Letters* 1998;72:903–905.
11. Yu J, Namba Y. Atomic surface roughness. *Applied Physics Letters* 1998;73:3607–3609.
12. Ferguson B, Zhang XC. Materials for terahertz science and technology. *Nature Materials* 2002;1:26–33.
13. Flannery CM, von Kiedrowski H. Effects of surface roughness on surface acoustic wave propagation in semiconductor materials. *Ultrasonics* 2002;40:83–87. [PubMed: 12160054]
14. Sherwin M. Applied physics: Terahertz power. *Nature* 2002;420:131–133. [PubMed: 12432371]
15. Shekhawat GS, Dravid VP. Nanoscale imaging of buried structures via scanning near-field ultrasound holography. *Science* 2005;310:89–92. [PubMed: 16210534]
16. Fang N, Lee H, Sun C, Zhang X. Sub-Diffraction-Limited Optical Imaging with a Silver Superlens. *Science* 2005;308:534–537. [PubMed: 15845849]
17. Chiu KY, Cheng FT, Man HC. Evolution of surface roughness of some metallic materials in cavitation erosion. *Ultrasonics* 2005;43:713–716. [PubMed: 16126092]
18. Mitri FG, Eberlein U, Fatemi M. Surface roughness imaging using the acoustic emission induced by the dynamic radiation force of ultrasound. *Applied Physics Letters* 2006;88:234105.

Fig. 1.
Geometry of the acrylic test block.

Fig. 2.

(Color online) CWUR system setup. The transducer is focused on the surface of the object. The reflected ultrasound beam is detected by the same transducer. The image is formed by scanning the surface of the object while recording the voltage variations due to phase changes. The experiments take place in a water tank containing the transducer and the object. The object (acrylic block) is secured on a plate attached to a three-axis positioning system for the scanning process.

Fig. 3.
CWUR image of the block surface corresponding to an area of $12 \times 80 \text{ mm}^2$.

Fig. 4.
A one-line profile of the CWUR image of the block surface. Voltage variations due to the surface roughness are well displayed for the steps and the ramp.

Fig. 5.

A quantitative one-line profile of the CWUR image of the block surface. Surface roughness in micron-scale variations are identified in addition to the ramp height on the right-hand side of the figure.

Table 1

Measurement values of surface roughness as obtained by the CMM and CWUR.

Surfaces (Fig. 1)	CMM	CWUR	Percent error
a-f	0.135°	0.1166°	13.63 %
a-b	4.22 μm	4.5 μm	6.22 %
b-c	17.3 μm	12.7 μm	26.6 %
c-d	16 μm	16.3 μm	1.84 %
d-e	19.05 μm	17.3 μm	9.19 %