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Short Communication

Continuous-wave ultrasound reflectometry for surface roughness imaging applications

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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 non-contact 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%.

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 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 non-contact measurement and inspection of surface roughness [5].

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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

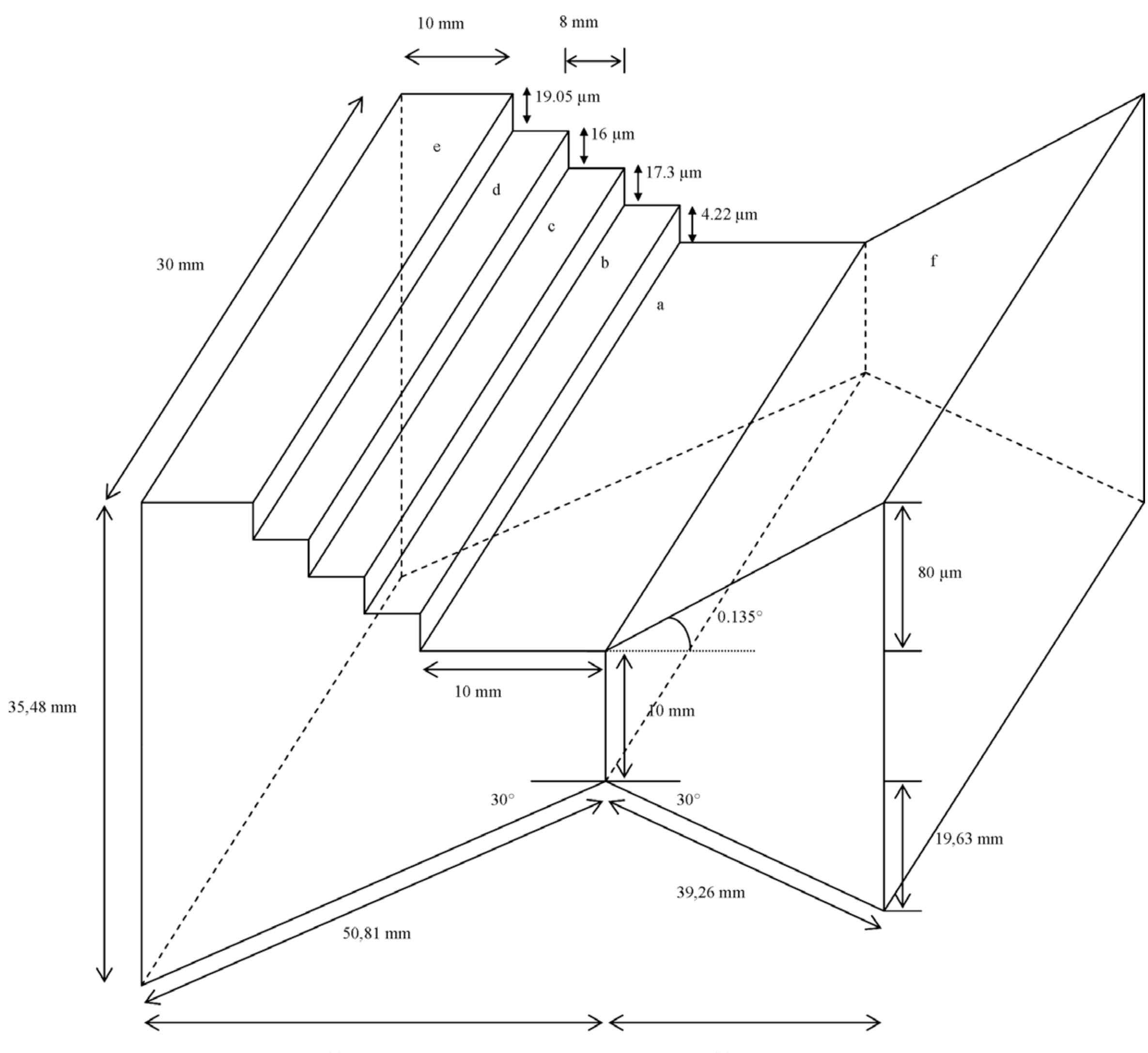

Fig. 1. Geometry of the acrylic test block.