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Characterization of Skewed Rough Surface by Air-coupled Ultrasound

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1. Introduction

Characterization of topographic roughness of a material surface is important in many fields of engineering such as tribology, contact mechanics, optics and bio-application.[1)] Although so-called stylus profilometry is well known and widely employed for measuring surface roughness, the method is not always acceptable for some practical uses because it is a contact technique and therefore, difficult to use in in-situ or on-line measurements. It is required to develop any alternative methods to overcome such drawback.

Ultrasonic method has been proposed as one of the alternative methods to characterize surface roughness.[2-4)] In such ultrasonic methods, the surfaces to be evaluated are assumed to be random rough surfaces having Gaussian distributed height profiles. However, material surfaces polished mechanically or treated chemically often have an asymmetrical distribution of the height profile of the surface. Nevertheless, the effect of such asymmetrical distribution of height profile on the ultrasonic roughness evaluation has not been studied. In this work, an air-coupled ultrasound at frequency around 0.4 MHz has been applied to characterization of a series of sandpapers having asymmetrically distributed height profiles for a wide range of roughness. The effects of the non-Gaussian height distribution on the reflected amplitude from the surface are then examined.

2. Theory

Kirchhoff-based scattering model has been used to study wave scattering phenomena from random rough surface having Gaussian distributed height surface. When an elastic wave is reflected from a rough surface, the overall scattered field consists of coherent and incoherent components. The present study focuses on the coherent component. At normal specular angle (incident angle, θ_i = reflected angle, $\theta_r = 0°$), the intensity of the coherent component I_{coh} is given by[5)]

$$I_{coh} = I_0 \exp(-2k^2 Rq^2) \qquad (1)$$

where I_0 is the reflected wave intensity from a perfect smooth surface, k is the wavenumber and Rq is the root-mean-square roughness.

The measure of asymmetry of the height distribution of the surface profile is called skewness, Rsk, and is given as[6)]

$$Rsk = \frac{1}{NRq^3} \sum_{i=1}^{N} h_i^{\,3} \qquad (2)$$

where h and N are the deviation of surface point from the mean value of height and the number of data points, respectively. Depending on the distribution of the surface, the value of skewness may vary as shown in **Fig. 1**. Bulmer[7)] suggested a rule of thumb for skewness i.e. $Rsk \leq |0.5|$ as approximately symmetry, $|0.5| < Rsk \leq |1.0|$ as moderately skewed and $Rsk > |1.0|$ as highly skewed.

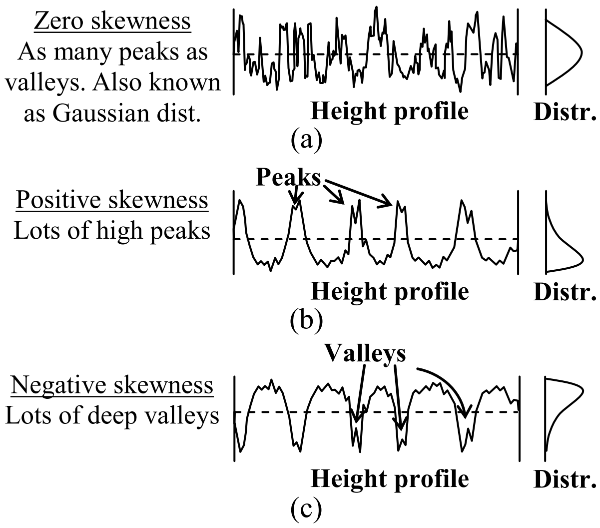

Fig. 1 Three different types of skewness.

3. Experiment

Fig. 2 shows the measurement system used in this work. Ten kinds of sandpapers with different grit sizes have been used as the specimens. The surface profile of each specimen is measured by a stylus profiler based on ISO 4288:1996 specifications and the Rq and Rsk values are calculated from the surface profiles. An acrylic plate with a very smooth surface of Rq = 0.02 µm is used as a reference specimen for normalization. A 0.4 MHz air-coupled ultrasonic transducer having center frequency of 0.35 MHz is used in pulse-echo mode at normal measuring angle. The distance

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between the specimen and the transducer is 30 mm. The average values of the reflected amplitudes at different locations are used for discussion.

4. Results and Discussion

Fig. 3 shows the comparison between the amplitudes measured ultrasonically at 0.35 MHz and theoretical ones. The reflected amplitude from each specimen is normalized with that reflected from the reference specimen. As can be seen from the results, the normalized amplitudes reflected from the specimens having approximately symmetrical or Gaussian distribution of height (denoted by black circles) almost agree with the theoretical ones while those that reflected from the specimens having moderately skewed rough surface deviate from the theoretical ones.

Using the normalized amplitude in **Fig. 3**, surface roughness Rq_{UT} are ultrasonically estimated from equation (1) and then compared with those measured by a stylus profiler, as shown in **Fig. 4**. It is found that regardless of roughness, surface with approximately symmetry height distribution ($Rsk < |0.5|$) tends to cause ±10% of errors to the estimated Rq_{UT} while moderately skewed rough surface ($|0.5| < Rsk \leq |1.0|$) tends to make the estimated Rq_{UT} smaller than Rq_{SP} up to approximately 30%. These results also reveal that for a skewed height profile with a lot of high peaks or deep valleys, a reflection surface with relatively smaller Rq value than the measured Rq_{SP} is dominant in the ultrasonic measurements. This fact also explains the reason that the reflected amplitudes from skewed rough surfaces become larger than the expected values from the theoretical calculations as shown in **Fig. 3**.

5. Conclusions

In summary, the characterization of skewed rough surface of sandpapers has been demonstrated using a 0.4 MHz air-coupled ultrasonic transducer. It has become apparent that regardless of roughness, asymmetry in terms of skewness of the height distribution causes errors in the ultrasonic roughness measurement results. It is hoped that theoretical analysis to investigate wave scattering from a skewed surface will be developed to improve the ultrasonic surface topography evaluation.

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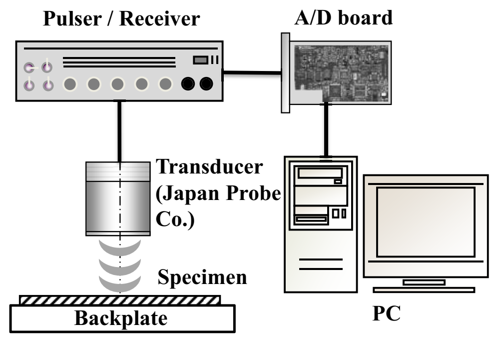

Fig. 2 Experimental setup.

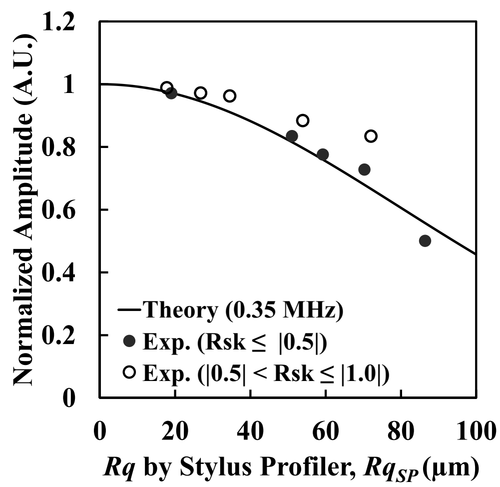

Fig. 3 Variations in the reflected wave amplitude with surface roughness Rq.

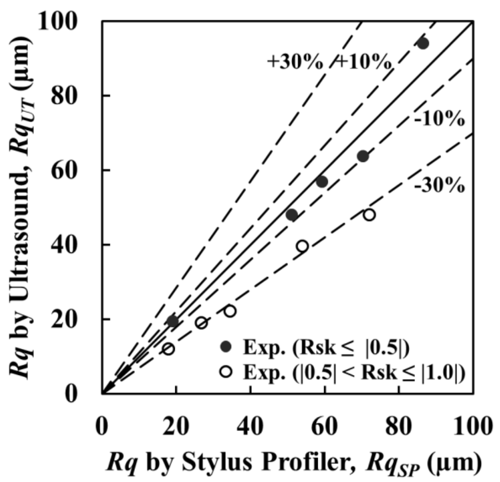

Fig. 4 Comparison between Rq_{UT} and Rq_{SP}.