# ACOUSTIC MICROSCOPY MEASUREMENTS TO CORRELATE SURFACE WAVE VELOCITY AND SURFACE ROUGHNESS

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## INTRODUCTION

Acoustic microscopy can be used for very localized measurements of the velocity and attenuation of surface waves, and hence is a possible technique for nondestructive evaluation of near surface damage due to fatigue, machining, friction, wear, etc. Because the frequency of operation of an acoustic microscope is high, usually above 100 MHz, the wavelength of the surface wave is relatively small, and thus the roughness of the specimen may affect the wave velocity. In most cases the specimens must be polished to a metallurgical level to ensure that the true Rayleigh wave velocity, i.e., the one for a smooth surface will be measured. For some cases the specimens should, however, not be polished. For example, for the prediction of fatigue life, the roughness may increase during the fatigue test. Usually there remains a certain amount of roughness on the surface after friction, wear or machining. Polishing or any other surface preparation process may destroy the true surface condition of the specimen. Therefore, measurements should often be made for specimens with rough surfaces and it is then important to know the effect of surface roughness on the surface wave velocity in order that roughness effects can be distinguished from the effects that are of actual interest in the measurement.

In this paper the effect of surface roughness on the velocity of surface waves has been investigated using a line-focus acoustic microscope. The use of the line-focus acoustic microscope to measure the velocity and attenuation of surface waves has been discussed in considerable detail by Kushibiki and Chubachi [ 1 ]. The technique is based on the measurement of the V(z) curve, which is the record of transducer voltage output, V, with the variation of the distance, z, between specimen and acoustic lens. The surface wave velocity can be obtained from the periodic variation of the V(z) curve [ 2 ] . For a smooth surface, the V(z) curve has been calculated analytically by Somekh et al.[ 3 ] and Li et al.[ 4 ], based on the Fourier optics approach.

In order to predict theoretically the effect of the roughness, the surface wave velocity for a rough surface has been calculated by the method of Li and Achenbach [ 5 ], which extends the V(z) theory for a smooth surface to that for a sinusoidal surface. Obata et al.[ 6 ] reported measurements of the surface roughness effect on the surface wave velocity, but they considered only the vertical scale of the surface profile. In the present paper, the surface roughness has been characterized in terms of two parameters ; namely the average roughness ( vertical scale ) and the correlated length ( horizontal scale ). The correlation between these parameters of the roughness and the surface wave velocity measured by acoustic microscopy has been examined. The configuration of the problem under consideration is shown in Figure 1. The surface of the specimen is irregularly rough.

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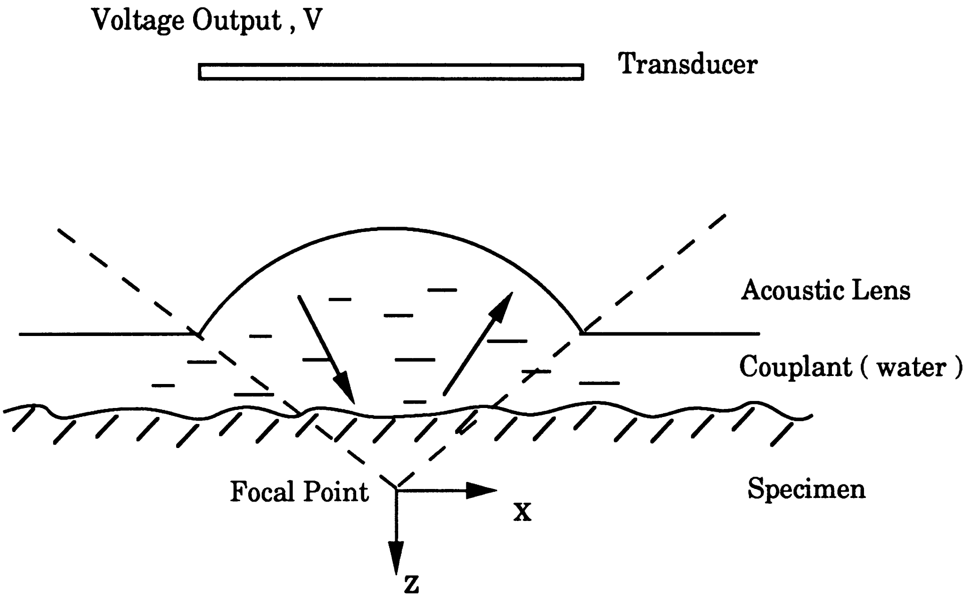

Fig.1 The configuration of the acoustic probe and the specimen with a rough surface.

The experimental results obtained for aluminum specimens have been compared qualitatively with theoretical results.

## THEORETICAL CALCULATION

Somekh et al. [ 3 ] have given the following integral expression for V(z),

$$V(z) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \exp[\, i(k_z z + k_z' z)\,] \cdot L_1(k_x') \cdot L_2(k_x) \cdot S(k_x, k_x')\, dk_x'\, dk_x \qquad (1)$$

where $k_z = (k_w^2 - k_x^2)^{1/2}$ , $k_z' = (k_w^2 - k_x'^2)^{1/2}$
and $k_w$ = wave number in water.

The functions $L_1(k_x')$ and $L_2(k_x)$, which are the angular spectrum functions of the acoustic lens, have been determined by Li et al.[ 4 ] for a line-focus acoustic lens. The reflection function $S(k_x, k_x')$, which is dependent on the material properties and the surface profile of the specimen, has been obtained by Li and Achenbach [ 5 ] for a sinusoidal surface by using the Rayleigh method.

In the present paper, the surface profile has been modeled as a triangular sawtooth profile instead of a sinusoidal one. The sawtooth profile is considered close to real surface roughness because it contains more high frequency components in the frequency domain. For the calculation of V(z) curves, the method of Ref.[ 5 ] has been used except that a FFT approach for the calculation of $S(k_x, k_x')$ has been adopted in order to increase the calculation efficiency, as suggested by Berman and Perkins [ 7 ]. Numerical results calculated for sawtooth profiles of various periods and heights are shown in Figure 2. The height of the surface profile for this calculation is much smaller than the wavelength ( 13μm ) of a surface wave on an aluminum surface at 225 MHz. In figure 2 the surface

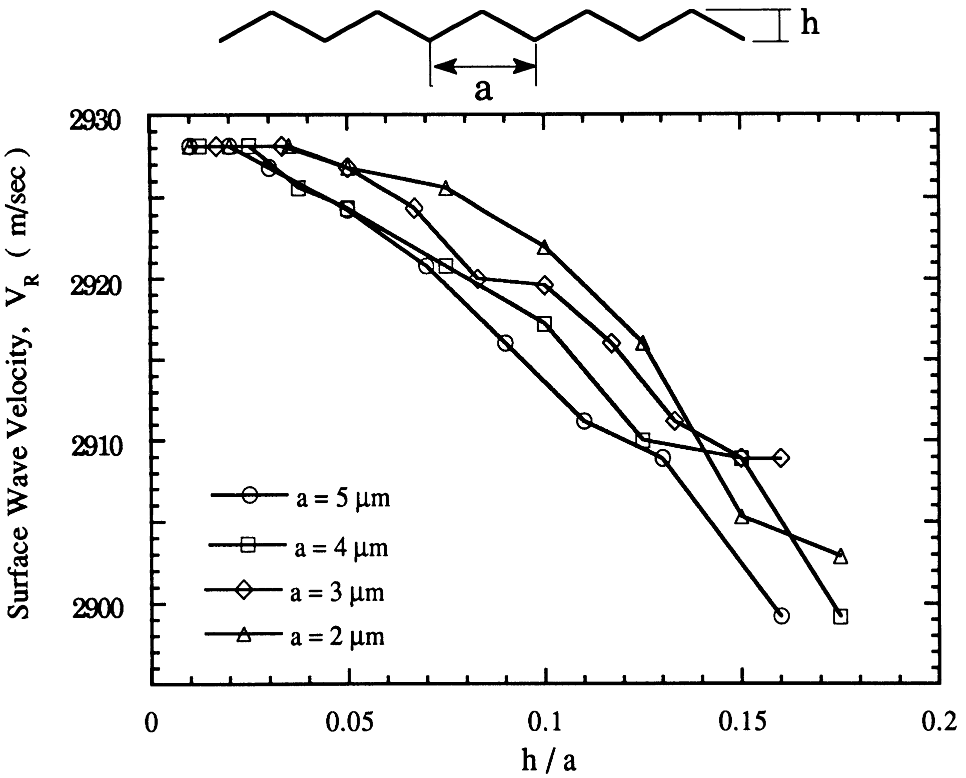

Fig.2 Surface wave velocity calculated for the sawtooth surface profile of various periods ( a ) and heights ( h ).

wave velocity is displayed as a function of the ratio of the height to the period, h/a. It is noted that the surface wave velocity decreases as the value of h/a increases. The surface wave velocity shows a quite linear change as the ratio h/a increases.

## CHARACTERIZATION OF ACTUAL SURFACE ROUGHNESS

Figure 3 shows a schematic representation of a rough surface with its vertical scale exaggerated. The roughness is usually treated as a random number $x_i$, which is the surface height variation from the mean level, measured at discrete points with equal transverse spacing, $\Delta t$. The statistical parameters of the random number $x_i$ are then used to describe the surface roughness. It is obvious that to characterize the surface roughness both vertical and horizontal characteristic lengths of the rough surface should be determined.

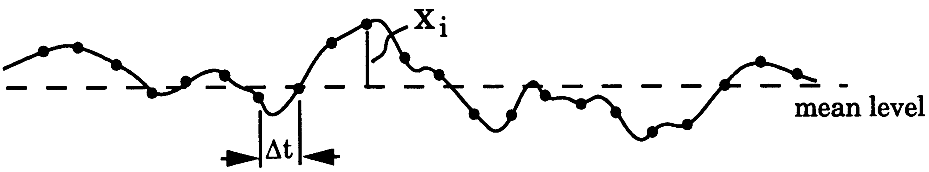

Fig.3 A schematic representation of a rough surface.

## Vertical Scale

Two parameters have been widely used to characterize the vertical scale of the roughness, namely the root-mean-square roughness, $R_{rms}$, and the average roughness, Ra. Here the average roughness is used because, according to Bennett and Mattsson [ 8 ] , it is normally used for roughness of machined surfaces. By definition, Ra is simply the average of the absolute value of the surface height variation. Expressed in equation form, we have

$$Ra = \frac{1}{N}\sum_{i=1}^{N} | x_i | \qquad (2)$$

## Horizontal Scale

The horizontal characteristic length of the roughness had received little attention because it is more difficult to determine as discussed by Church [ 9 ]. Here the 1/e correlated length based on the autocorrelation function had been chosen as the horizontal scale length. The autocorrelation function, $R_{xx}(\tau)$, of a random variable $x_i$ is defined as,

$$R_{xx}( \tau = m\Delta t ) = \frac{1}{N}\sum_{i=1}^{N-m} x_i \cdot x_{i+m} \qquad (3)$$

where $\tau$ is called the lag length. The correlated length, Lc, as used here is the value of the lag length at which the autocorrelation function drops to 1/e ( 0.368 ) of its value at zero lag length. Figure 4 shows a typical normalized autocorrelation function of a rough surface and its 1/e correlated length, Lc.

## EXPERIMENTAL PROCEDURE AND RESULTS

The material used for the experiment is aluminum 2024-T351. Each specimen was first prepared as for a standard metallurgical test, namely by polishing with #240, #320, #400, #600 SiC abrasive paper and by lapping with 6μm and 1μm diamond particles in a slurry with mineral oil as lubricant. The specimens were then rubbed slightly and unidirectionally against various SiC abrasive papers from #240 to #2000 to have different surface roughnesses.

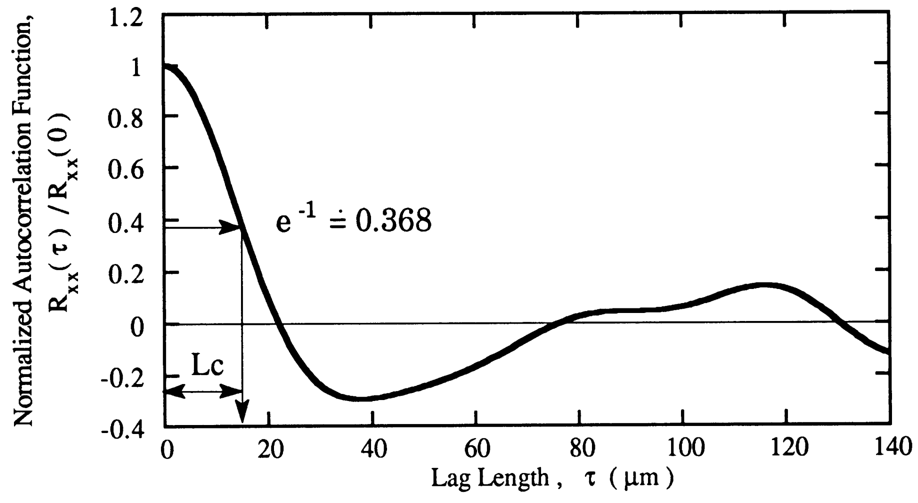

Fig.4 Autocorrelation function and 1/e correlated length for a rough surface.

Table I Experimental results of the roughness parameters and the surface wave velocity.

| Specimen | Surface roughness | | | Surface wave velocity, $V_R$ (m/s) | |
|---|---|---|---|---|---|
| No. | Ra (mm) | Lc(mm) | Ra/Lc | Average | Std. Dev. |
| 1 | | | | 2928 | 1.1 |
| 2 | 0.038 | 14.1 | 0.0027 | 2925 | 1.2 |
| 3 | 0.074 | 5.0 | 0.0148 | 2912 | 1.1 |
| 4 | 0.08 | 6.5 | 0.0123 | 2909 | 1.1 |
| 5 | 0.09 | 4.6 | 0.0196 | 2907 | 1.4 |
| 6 | 0.12 | 9.7 | 0.0124 | 2916 | 1.1 |
| 7 | 0.13 | 22.1 | 0.0059 | 2921 | 1.0 |
| 8 | 0.14 | 6.4 | 0.022 | 2910 | 1.7 |
| 9 | 0.21 | 6.9 | 0.0304 | 2896 | 2.0 |
| 10 | 0.23 | 6.7 | 0.0343 | 2894 | 2.2 |
| 11 | 0.25 | 6.3 | 0.0397 | 2895 | 2.4 |
| 12 | 0.27 | 11.4 | 0.0237 | 2906 | 2.8 |
| 13 | 0.27 | 10.5 | 0.0257 | 2904 | 1.9 |

The roughness parameters, Ra and Lc , were measured in the direction perpendicular to the polishing direction by the use of a Taylor-Hobson Surtronic 3P profiler. The total sampling distance was 0.7 mm and the number of sampling points 2048. The Ra and Lc values were taken as the average values of 5 measurements for each specimen. The surface wave velocity was measured along the direction perpendicular to the polishing direction at 40 different locations for each specimen. Because the measurement of the surface wave velocity by the acoustic microscope is very localized, it is necessary to take the average value. The measurement results of the roughness parameters and the average value of 40 measurements of the surface wave velocity, $V_R$, are listed in Table I. The standard deviation of the average value of the surface wave velocity are also listed. Specimen No.1 is carefully polished to be a mirror surface specimen for which the roughness was too small to be measured by the profiler.

The data listed in Table I are plotted in Figs. 5 and 6. In Figure 5, the measured surface wave velocity is displayed as a function of the vertical character of the surface roughness. The correlation coefficient between $V_R$ and Ra is about -0.8. In Figure 6, the measured surface wave velocity is displayed as a function of the non-dimensional roughness parameter Ra/Lc. The correlation coefficient between $V_R$ and Ra/Lc is as high as -0.97, indicates a good linear correlated relationship between them. It is noted from Figure 6 that the change of the surface wave velocity due to the roughness varies linearly with the parameter Ra/Lc.

## CONCLUSION

The effect of roughness on the velocity of surface waves has been investigated by line-focus acoustic microscopy. The surface wave velocity, $V_R$, for a number of aluminum specimens with a variety of surface roughnesses has been measured. Two parameters have been chosen to characterize the surface roughness, namely the average roughness, Ra, and the correlated length, Lc. The former represents the average height of the surface profile with respect to its mean level and the latter represents a transverse characteristic length of the profile. The experimental results show that the surface wave velocity is linearly correlated to the non-dimensional roughness parameter, Ra/Lc. The velocity drops as the value of Ra/Lc increases. The result are important for two reasons. In the first place they indicate how 'smooth' the specimen has to be prepared for an accurate measurement of the classical Rayleigh wave velocity. In the the second place if there exists a certain amount of roughness the results show how much the measured results will be affected by the roughness. A theoretical calculation for a sawtooth surface profile shows comparable result.

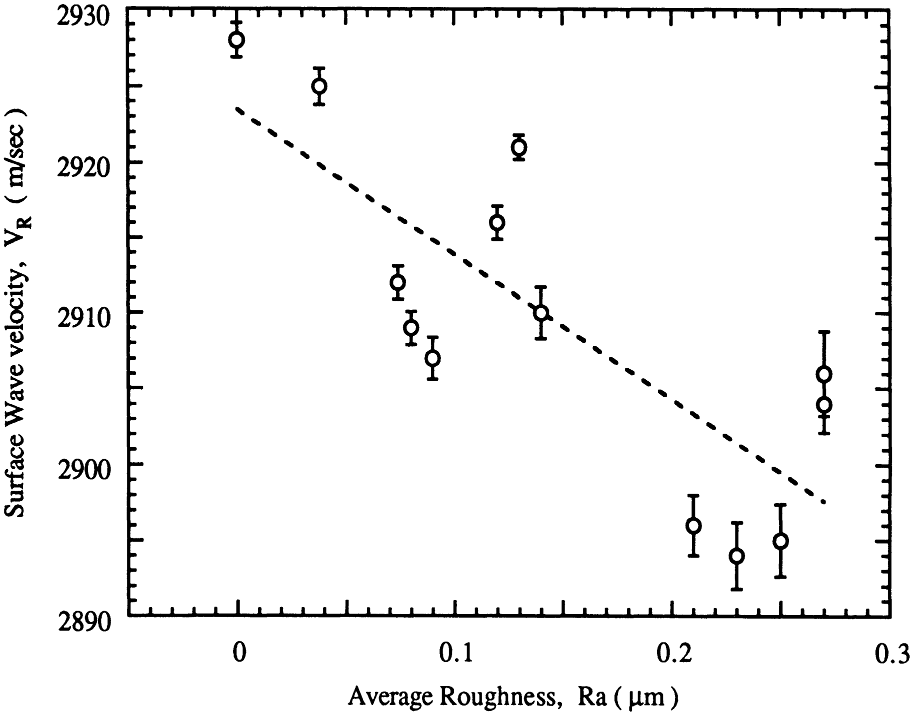

Fig.5 The correlation between the surface wave velocity and the average roughness.

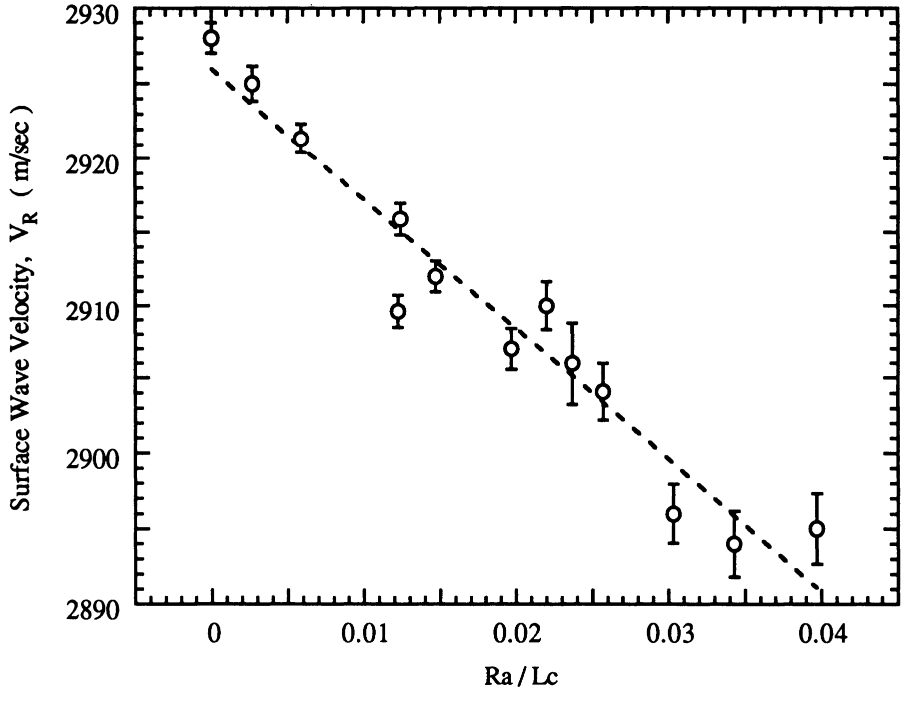

Fig.6 The correlation between the surface wave velocity and the nondimensional roughness parameter, Ra/Lc

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