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MEASUREMENT OF ACOUSTOELASTIC EFFECT OF RAYLEIGH SURFACE WAVES USING LASER ULTRASONICS

W-Y Lu and L. W. Peng
Materials and Engineering Sciences Center
Sandia National Laboratories
Livermore, CA 94551-0969

S. Holland
Electrical Engineering Department
Cornell University
Ithaca, NY 14853

INTRODUCTION

The acoustoelastic effect refers to the fact that elastic wave velocities vary with stress. Measurements of the change in stress-induced velocity yield information which leads to the determination of stresses. Some work has been done to explore the possibility of using ultrasonic waves, including bulk longitudinal and shear waves as well as surface waves, for the nondestructive evaluation of stresses. This paper focuses on Rayleigh surface waves, which have the advantage of detecting both surface stresses and stress gradients.

Piezoelectric or electromagnetic acoustic transducers have been used for the application of Rayleigh waves in the acoustoelastic measurement of stress [1-5]. The size of these transducers and their fixtures limit the distance between transducers. Sharp edge wedges are usually bound to the pick-up piezoelectric transducers, known as the Rayleigh or surface wave device (SWD), to provide a better spatial resolution when the stress field is not uniform. The smallest distance reported is 11 mm. On the other hand, acoustic miscroscopes (AM) can measure localized stress for a very small area, from 30 μm to 2 mm [6, 7]. Both SWD and AM method may lack the agility required for general applications.

Laser ultrasonics (LU) is a method for optical generation and detection of ultrasound. The generation and detection areas can be focused to very small spot sizes, less than 1 mm, which allow velocity measurements to be made over a path length of a few millimeters. The LU technique is noncontact and can be applied remotely; it has many potential applications. We used the LU technique to measure the acoustoelastic behavior of an aluminum alloy, Al6061-T6.

ACOUSTOELASTIC EQUATIONS

Assuming the solid is initially isotropic and uniformly stressed, the stress-induced velocity changes are

$$(v_1 - v_o) / v_o = k_1 \sigma_1 + k_2 \sigma_2$$
$$(v_2 - v_o) / v_o = k_1 \sigma_2 + k_2 \sigma_1 \qquad (1)$$

where v_1 and v_2 are the Rayleigh wave velocities in the principal stress directions x_1 and x_2, v_o is the isotropic Rayleigh wave velocity, σ_1 and σ_2 are the principal stresses, and k_1 and k_2 are stress-acoustoelastic constants.

DISCLAIMER

When the stress varies in the direction of depth x_3, the Rayleigh wave will be dispersive since the depth of penetration of the Rayleigh wave is proportional to the wave length. Consider a uniaxial, linear stress distribution in x_3 [1]

$$(v_1 - v_o) / v_o = k_1 \sigma_1 + (\beta_1 / \omega)(d \sigma_1 / d x_3) \quad (2)$$

where $\omega = 2\pi f$ denotes circular frequency, and β_1 is a constant. The stress gradient can be determined by measuring the Rayleigh wave velocity at two different frequencies f1 and f2

$$((v_1)_{f1} - (v_1)_{f2}) / v_o = b (d \sigma_1 / d x_3) \quad (3)$$

where $b = \beta_1 (1/\omega_1 - 1/\omega_2)$.

EXPERIMENTS

The experimental setup consists of three parts: the LU system for generating and detecting ultrasonic waves, the data acquisition and analysis system to measure the time-of-flight (TOF) of a wave between two points, and the mechanical system for loading samples.

LU Setup

A schematic of the LU setup is shown in Figure 1. A pulsed laser generates ultrasonic waves by rapidly heating a point (or a line) on the sample. A continuous wave (CW) laser illuminates a point on the sample; the reflected light is collected through a lens for the interferometer to detect the surface displacement. This is the typical single point detection scheme. One drawback of this simple method is that the jitter from the trigger signal, from either the synchronized output of the pulsed laser or the photodiode trigger, causes inconsistent TOF results.

To eliminate the problem of jitter caused by the trigger signal, a two-point detection method was developed. As shown in Figure 2, the detection beam is reflected twice from the sample and then fed to the interferometer. The interferometer output waveform is the sum of waveforms at two points, which behaves as if there are two receivers although only one interferometer is used. TOF can be accurately determined between the two measurement points, instead of relative to the excitation laser pulse. This two-point detection method requires a mirror-like surface finish at the reflection points.

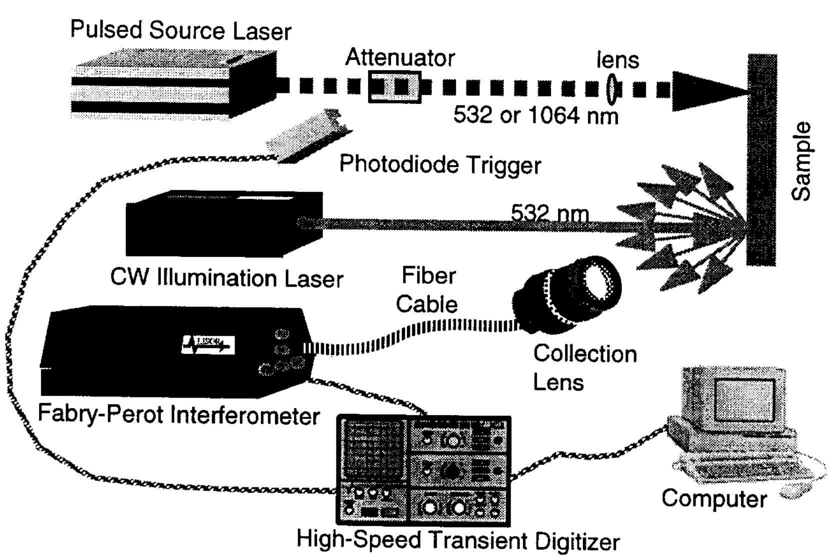

Figure 1. A schematic of the LU and data acquisition setup.

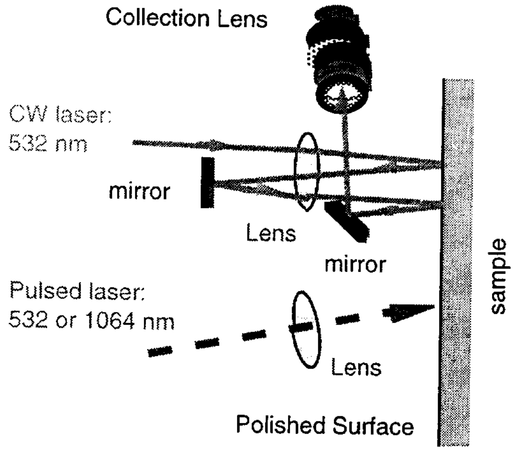

Figure 2. Two point detection.

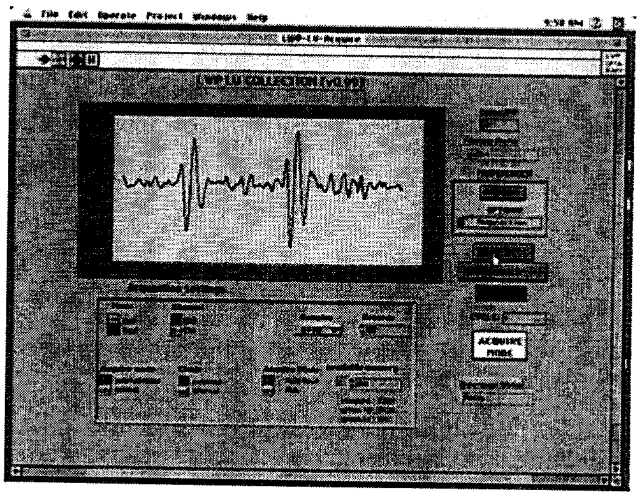

Figure 3. The panel of the LabVIEW VI and a typical waveform of two-point detection.

TOF Measurement

The data acquisition and analysis equipment is also shown in Figure 1. Ultrasonic waveforms were digitized at 1 GHz using a TEK RTD720. A LabVIEW virtual instrument (VI) was developed to control data acquisition, Figure 3. The VI allows repetitive measurement, record averaging, and saving. MatLab programs were developed for post-experiment signal processing. The TOF measurement was calculated by the cross correlation technique.

Mechanical Loading Systems

Both tensile and bending tests were performed. The tensile test was used to obtained the acoustoelastic constant k_1 of equation (1), while the bending test was used to investigate the effect of stress gradient. Figure 4 shows a picture of the custom made loading frame with a tensile specimen in place. The loading frame is mounted on an x-y-θ_Z stage, so we can make various LU measurements without disturbing the stress state of the sample and the optical path. The thickness of the tensile specimen is 3.18 mm (1/8"). The gage length is greater than 76 mm (3"). The four-point bending setup is shown in Figure 5. Within section BC, the stress gradient is uniform. Piezoelectric transducers, 2.25 and 5.0 MHz, were used to generate surface waves; LU was used in detection only. Beam thickness and width are 3.18 mm (1/8") and 22.2 mm (7/8"), respectively.

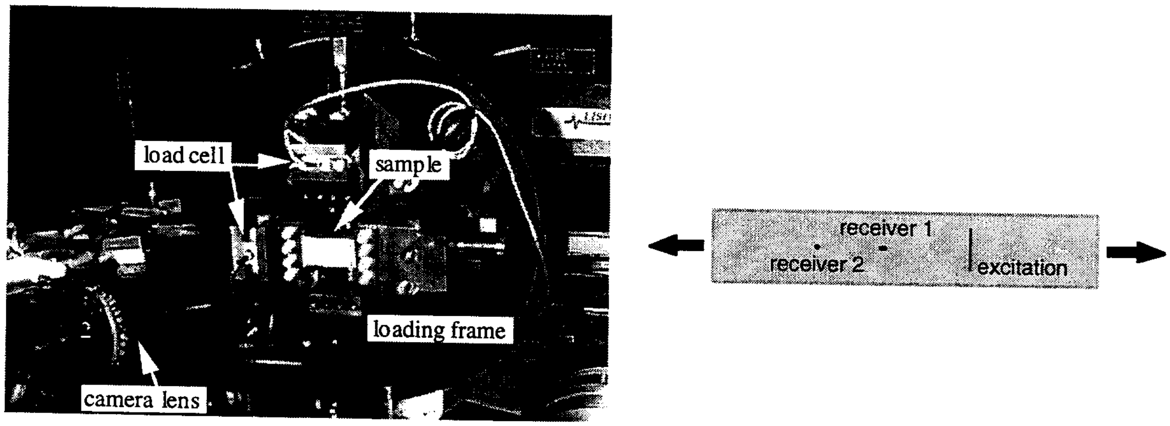

Figure 4. The tensile loading system.

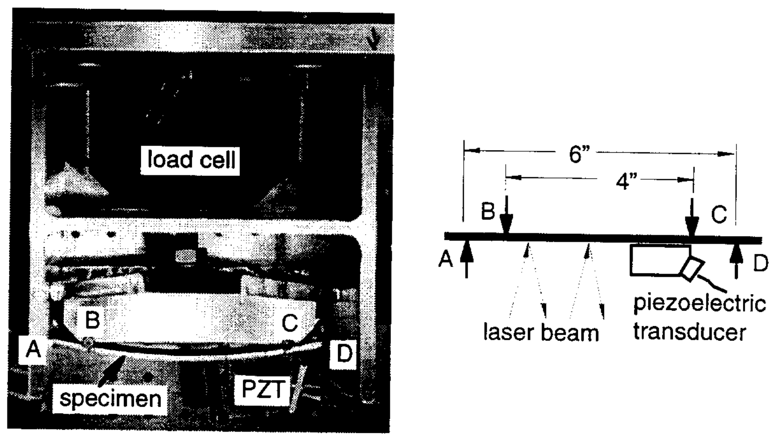

Figure 5. The four-point bending setup.

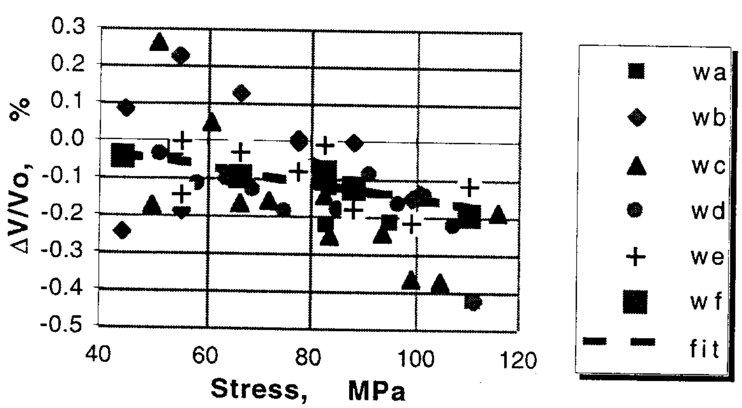

Figure 6. Acoustoelastic effect of Al6061-T6. The direction of wave propagation is parallel to the direction of loading. The loading of experiments wa through wf were the same but different data acquisition parameters were used, which are listed in Table 1.

RESULTS AND DISCUSSION

The relative changes in the surface wave velocity measured from uniaxial tensile tests of aluminum 6061-T6 are shown in Figure 6. Experiments were repeated under various measuring conditions as listed in Table 1. Consider the 'wf' experiment, the distance d between two receiving points was 15 mm; the time was the average of 20 TOF measurements; each TOF was determined from the average of 32 waveform records. When the time was determined with only one TOF measurement, such as wa, wb and wc, the scatter is larger than the acoustoelastic effect. It is known that LU has a lower sensitivity compared to the conventional piezoelectric technique. A large number of averages is needed to improve the signal-to-noise ratio. The wf data has the least amount of scattering and was fitted by the dotted line in Figure 6.

A comparison with previously determined results of aluminum alloys from various investigators and techniques are listed in Table 2. The value of k_1 varies from -1.1 to -3.3 x10^{-5} / MPa. It has been suggested that this may be attributed to the difference of the penetration depth of the surface wave [8], or the different dislocation structures resulting from manufacturing the sample [2].

A recent study of texture effects on acoustoelastic behavior of aluminum alloys by Man [12] showed very interesting results. For the isotropic case, k_1 = -.0134/GPa and k_2 = .0091/GPa. For the anisotropic case, k_1 and k_2 will be in the RD and TD, respectively. The explicit formulae were derived, which give the anisotropic part of k_1 and k_2 in terms of the texture coefficients W400,...,W660. It turns out that texture affects k_1 and k_2 significantly. The value of k_1 is found to vary in a narrow range, namely from -0.0214 to -0.0239, and k_2 is found to vary from 0.0060 (purely rolling texture) to 0.0224 (purely recrystallization texture). These findings are consistent with the experimental results.

The result of the bending test is shown in Figure 7. The square and triangular marks represent the first and second loading paths of the experiment, and the specimen is completely unloaded between two paths. The dotted line is the best fit of the experimental data. The value Δt is the relative time change of two different frequencies traveling on the same wave path, $\Delta t = t_{5.0MHz} - t_{2.25 Mhz}$. We made LU measurements on the tension side of the beam. The surface stress is uniform, which is $\sigma_{surface} \approx 1.6*(d\sigma/dz)$ MPa. Since the 2.25 MHz wave has a longer wavelength and penetrates deeper into the surface, the average stress of the affected layer is lower than that of 5.0 MHz wave. According to equation (1) and the negative k_1 value, the 2.25 MHz wave has a faster velocity (or shorter TOF). This is consistent with the experimental results. Ideally, the line should pass the origin. It is possible that there are residual stresses due to surface preparation. This needs further investigation.

Table 1. Acoustoelastic parameter k_1 obtained from LU measurement

Experiment	d, mm	# of TOF	# of Record	k_1, 10^{-6}/MPa
wa	9	1	64	-7.5
wb	9	1	64	-3.7
wc	9	1	64	-4.7
wd	15	3	32	-1.9
we	15	3	32	-3.2
wf	15	20	32	-2.2

Table 2. Comparison of experimental results

Aluminum alloy	Experimental method	distance (mm)	k_1 (10^{-5} / MPa)	k_2 (10^{-5} / MPa)	Reference
6061-T6	LU	15, 9	-2.2		present work
A2017T3	AM	0.03 - 0.115	-2.4	0.74	[8]
6061-T6	AM	1 - 2	-1.9	0.7	[7]
B95T	SWD		-3.3		[9]
6061-T651	SWD	26	-1.2	0.88	[2]
2024-T351	SWD	11	-1.1	0.75	[10]
6061-T6	SWD		-1.7		[11]

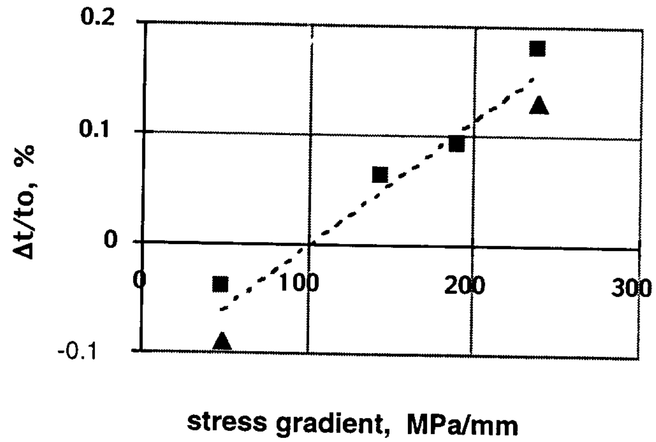

Figure 7. The results of the bending test show the relationship between relative time changes between 2.25 and 5 MHz surface waves and stress gradient.

CONCLUSIONS

Laser ultrasonics has been applied to measure the acoustoelastic behavior of aluminum 6061-T6. Two types of test have been performed: uniaxial tensile tests to determine the acoustoelastic constant k_1, which has been found to be $-2.2x10^{-5}$ / MPa, and bending tests to evaluate the surface stress gradient of the specimen. The experimental results are consistent with theoretical predictions.

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