Available online at www.sciencedirect.com
SCIENCE DIRECT®
Spectrochimica Acta Part B 58 (2003) 1171–1175
SPECTROCHIMICA ACTA
PART B
www.elsevier.com/locate/sab

Determination of linear and nonlinear elastic parameters from laser experiments with surface acoustic wave pulses☆

H.A. Schuessler, S.N. Jerebtsov, A.A. Kolomenskii*

Department of Physics, Texas A&M University, College Station, TX 77843-4242, USA

Received 7 July 2002; accepted 28 January 2003

Abstract

Time resolved laser techniques enabled the study of the nonlinear evolution of surface acoustic wave (SAW) pulses of very high-amplitudes with acoustic Mach numbers of approximately 0.01. In such waves even shock fronts can be formed during their propagation. Changes of the shape of intense SAW pulses provide information on the nonlinear acoustic parameters and the nonlinear elastic constants of the material. Measurements in polycrystalline stainless steel have shown that a compression of the nonlinear SAW pulse takes place in this metal material yielding a positive parameter of the local nonlinearity. The changes of the SAW pulse shape were calculated using a nonlinear evolution equation and the nonlinear acoustic parameters were determined by fitting the evolution equation to the experimental data. The attenuation of SAWs was determined by measuring low amplitude pulses. In addition, the velocities of longitudinal and shear waves were obtained by registering the precursors of bulk waves at the surface.

Keywords: Nonlinear surface acoustic waves; Nonlinear evolution equation; Pulse compression; Shock front; Laser photoacoustics

1. Introduction

Surface acoustic waves (SAWs) propagate along the surface of a solid and produce strains, decaying exponentially from the surface inward the material. They can exhibit large energy densities due to their confinement into the narrow subsurface region, which is of the order of one wavelength in depth. When strongly excited, SAWs will drive the medium into the nonlinear elastic regime. Therefore, as an intense SAW propagates the evolution of the wave shape in time allows us to obtain information on nonlinear acoustic parameters, and in this way the higher order nonlinear elastic constants of the material. In the last few years such studies [1–4] have emerged mainly by employing efficient ways to couple the energy of the laser pulse to the surface by optimizing the absorption of pulsed laser radiation and by simultaneously reducing other effects such as reflection, optical breakdown, and ablation. Other SAW excitation mechanisms, such as for instance by piezoelectric transducers or particle beams exist, but do

☆ This paper was presented at the International Conference on Laser Probing (LAP-2002), held in Leuven, Flanders, Belgium, July 2002, and is published in the Special Issue of *Spectrochimica Acta Part B*, dedicated to that conference.

*Corresponding author. Tel.: +1-979-845-7861; fax: +1-979-845-2590.
E-mail address: a-kolomenski@physics.tamu.edu (A.A. Kolomenskii).

0584-8547/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0584-8547(03)00069-7

not easily lend themselves to nonlinear wave generation.

There is a wide range of interest in SAWs, spanning on the laboratory scale from novel methods for elastic materials characterization, to contributing on a global scale in seismology to earthquake research. SAWs also found applications in signal processing devices. In addition, a novel surface cleaning technique [5] applicable to micro circuits makes use of the large accelerations of SAWs to shake off small particles from silicon wafers.

2. Experimental

The SAWs of this experiment were produced dominantly by absorption in a thin covering layer of aqueous carbon suspension and resulted in surface pressures of up to several giga Pascal. In such pulses acoustic Mach numbers reached $M \sim 0.01$ and formation of shock fronts was observed in the studied solid materials. To minimize geometrical SAW diffraction, we focused the laser pulse onto the surface in a narrow line approximately 10 μm in width and 8 mm in length. In the experiment a Q-switched Nd:YAG laser with a variable pulse energy of up to 1.3 J, pulse duration 8 ns, and wavelength of 1.06 μm was used for excitation. For detection a dual-probe-beam technique was employed and enabled us to observe nonlinear transformations in a single laser excited SAW pulse. The calibration procedure of the setup is described in Ref. [1].

3. Theoretical model

The correct theoretical description of nonlinear SAWs has been a long standing problem. Two comprehensive approaches were developed recently for the description of nonlinear SAW pulses: one model uses the Hamiltonian formalism [6,7], and the other approach is based on the evolution equation [8,9] describing changes of the surface velocities in SAWs with propagation distance. The latter approach gives a consistent description of nonlinear SAWs without any a priori assumptions on the decay of the velocity into the depth of the solid and permits a rather simple interpretation of the results using three nonlinear acoustic constants.

The propagation velocity of high-amplitude acoustic waves depends on the particle velocity of the medium participating in the wave motion. This dependence leads to a nonlinear distortion of the wave profile. SAWs have two components: one corresponds to a shear wave with the polarization normal to the surface and to the propagation direction (normal component); the other component corresponds to a longitudinal wave and displacements in it are parallel to the unperturbed surface (in-plane component). These two components of a SAW pulse are connected through boundary conditions and related nonlocally by a Hilbert transform operator. The nonlinearity of the medium causes changes in the waveform of one component which depend also on the nonlinear interaction with the other component. As a result, for the description of the SAW nonlinearity, besides the usual local nonlinear term encountered in Burgers equation for bulk waves, also nonlocal terms should be taken into account. In order to describe the nonlinear propagation of a SAW in an isotropic solid three nonlinear acoustic constants must be introduced: one constant of the local nonlinearity and two constants of the nonlocal nonlinearity. The explicit expressions for these constants [9] contain elastic moduli of the second and third orders.

Taking into account attenuation the evolution equation for the in-plane component of the surface velocity v in the case of SAWs with a straight front can be presented in the spectral form [8]

$$C_R^2 \frac{\partial \bar{v}(x,\omega)}{\partial x} = \frac{(-i\omega)}{4\pi} \int_{-\infty}^{+\infty} \mathrm{d}\omega' \bar{v}(x,\omega') \bar{v}(x,\omega - \omega') \Big\{ \varepsilon_1 + \varepsilon_2 [1 - \mathrm{sgn}(\omega') \times \mathrm{sgn}(\omega - \omega')] + 2\varepsilon_3 \left(\frac{\omega - \omega'}{\omega} \right) \times [1 - \mathrm{sgn}(\omega) \mathrm{sgn}(\omega - \omega')] \Big\} - \alpha_0(\omega) c_R^2 \bar{v}(x,\omega) \tag{1}$$

where $\bar{v}(x,\omega) = \int \mathrm{d}\tau v(x,\tau) \exp(i\omega\tau)$ is the Fourier transform of the pulse profile, $\alpha(\omega)$ is the attenuation and c_R is the Rayleigh velocity. Eq. (1) was solved numerically and used in fitting procedure to determine the nonlinear acoustic parameters.

4. Results and discussion

The registration of the nonlinear changes in the surface particle velocities of aluminum, steel and fused silica is a result of our observations. As an example we show in Fig. 1 the time development of nonlinear compression in a SAW pulse for polycrystalline aluminum. The amplitudes of the surface velocity and the acoustic Mach number are $v_1 = 10$ m/s, $M_1 = v_1/c_R = 3.4\times10^{-3}$, $v_{n1} = 24$ m/s, $M_{n1} = v_{n1}/c_R = 8.2\times10^{-3}$ and $v_2 = 15$ m/s, $M_2 = v_2/c_R = 5.2\times10^{-3}$, $v_{n2} = 38$ m/s, $M_{n2} = v_{n2}/c_R = 1.3\times10^{-2}$, respectively, where the subscripts 1,2 correspond to the first and second probe spots. For aluminum the following set of nonlinear acoustic constants was determined: $\varepsilon_1 = 0.7\pm0.1$, $\varepsilon_2 = -1.02\pm0.01$ and $\varepsilon_3 = 2.5\pm0.5$ [4].

The mechanical forces associated with the large surface acceleration in high-amplitude SAWs can detach microparticles residing at the surface [5]. The surface acceleration of approximately 10^9 m/s^2 was reached (Fig. 1c) and corresponds to the removal of particles larger than approximately 0.2 μm. Consequently, this technique can be used for cleaning of surfaces from microparticles and for the determination of the Hamaker constant of the adhesion force.

Similar compression effects that we have observed for aluminum were also registered in copper. In addition we report here measurements performed for polycrystalline (austenitic) stainless steel. The pulses observed at two distances $x_1 = 5.2$ mm and $x_2 = 16.2$ mm are shown in Fig. 2. It should be noted that in polycrystalline metals attenuation is rather high in the megahertz frequency range. This attenuation was determined by comparing spectral amplitudes of low amplitude SAW pulses at two propagation distances and was approximated by the expression $\alpha(\omega) = \alpha_0\omega^2$, where $\alpha_0 \approx 1.1\times10^{-14}$/cm Hz^2.

The second order moduli were evaluated by measuring the propagation velocities of bulk waves from the signals of precursors [10] (Fig. 3). The

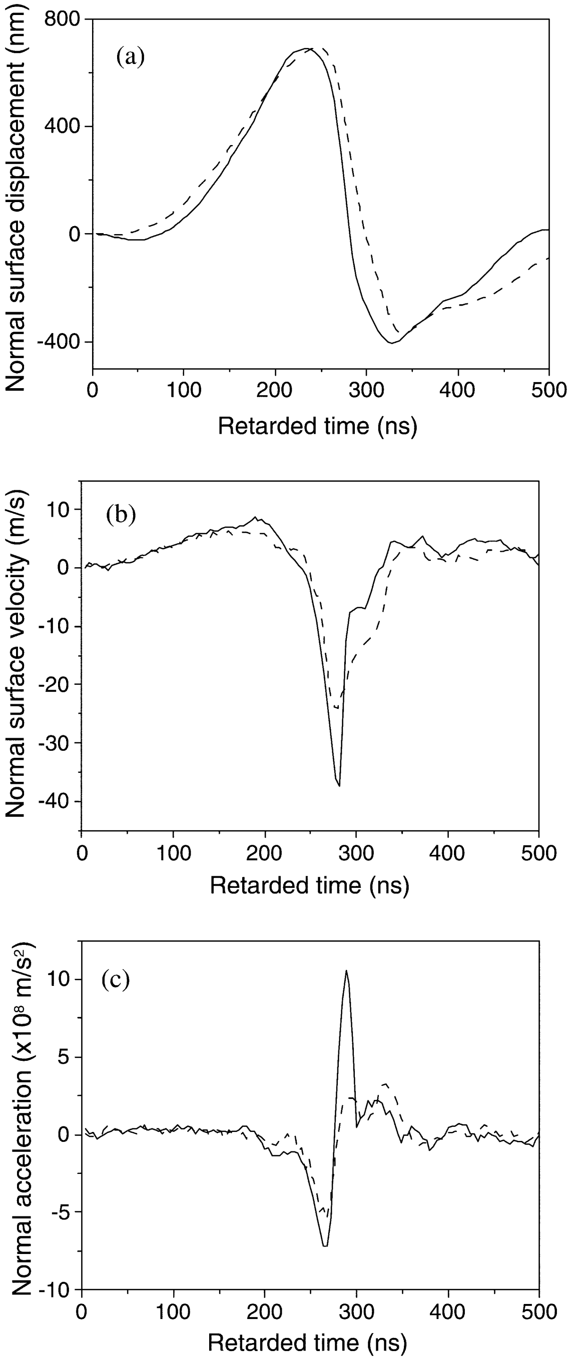

Fig. 1. SAW waveforms in aluminum for two propagation distances $x_1 = 13.8$ mm (dashed line) and $x_2 = 26.4$ mm (solid line). (a) Normal surface displacement; (b) normal surface velocity and (c) normal surface acceleration.

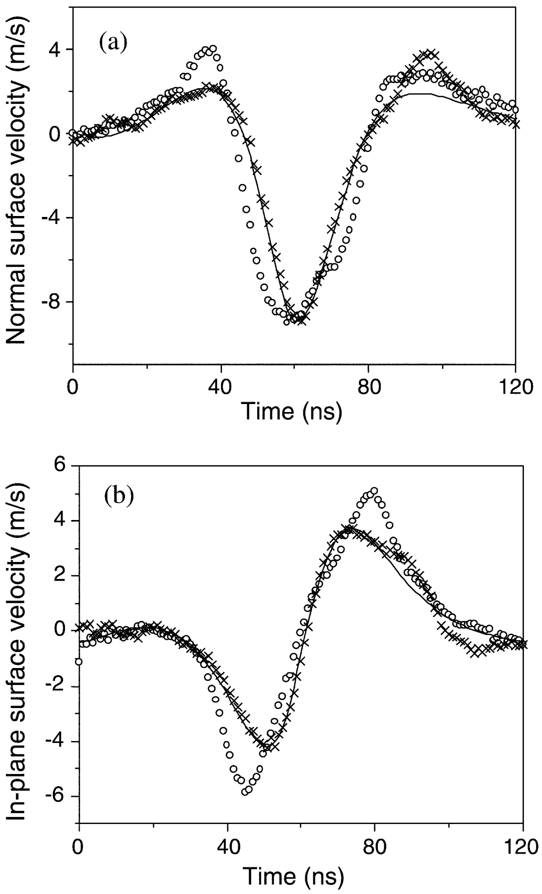

Fig. 2. SAW pulses registered in stainless steel at two propagation distances $x_1=5.2$ mm (open circles) and $x_2=16.2$ mm (crosses) from the excitation region: (a) normal surface velocity and (b) the calculated waveform of the in-plane surface velocity. The SAW pulse waveform calculated for x_2 using Eq. (1) with $\varepsilon_1=4.4$, $\varepsilon_2=-1.4$, and $\varepsilon_3=-2.5$ and the pulse shape at x_1 as the initial profile is shown as a solid line.

following parameters were determined experimentally: $c_l=(4500\pm50)$ m/s, $c_t=(3300\pm30)$ m/s, $c_R=(2850\pm30)$ m/s $\rho=(7.9\pm0.1)$ g/cm^3; consequently, for the elastic moduli of the second order we obtained: $c_{11}=(\rho c_l^2)\approx160$ and $c_{44}=(\rho c_t^2)\approx90$ GPa. The ratio of the propagation velocities has a relative error of about the ratio of the pulse duration to the propagation time, which was approximately 0.4% in this case. The solid curve in Fig. 2 represents the best fit calculated with $\varepsilon_1=4.4$, $\varepsilon_2=-1.4$, and $\varepsilon_3=-2.5$. The fitting procedure of the theoretical model of Eq. (1) to experimentally measured pulses was performed for five measured pairs of pulses and the average values of the nonlinear acoustic constants were evaluated as $\varepsilon_1=6\pm2$, $\varepsilon_2=0\pm2$, and $\varepsilon_3=3\pm2$. The values calculated from the data on the third order elastic moduli [11] were found to be $\varepsilon_1=5.2$, $\varepsilon_2=0.0$, and $\varepsilon_3=3.7$. The deviation of the experimental and theoretical values can be connected to individual variations of the material composition and the larger discrepancy for ε_3 can be due to the fact that the observed SAW pulse shape is relatively less sensitive to the variations of this parameter. It should be noted that in numerical simulation for periodic SAWs in steel [6] the formation of a narrow negative peak in the normal surface velocity was also obtained. This behavior corresponds to a positive parameter of the local nonlinearity as indeed follows from our data.

A different behavior, namely nonlinear wave stretching and additional down-conversion of the frequency, resulting in two sharp peaks in the vertical surface velocity and two corresponding shock fronts for the in-plane surface velocity was shown to occur in fused quartz and silica [1,4]. The acoustic parameter of the local nonlinearity (ε_1) is negative for these materials.

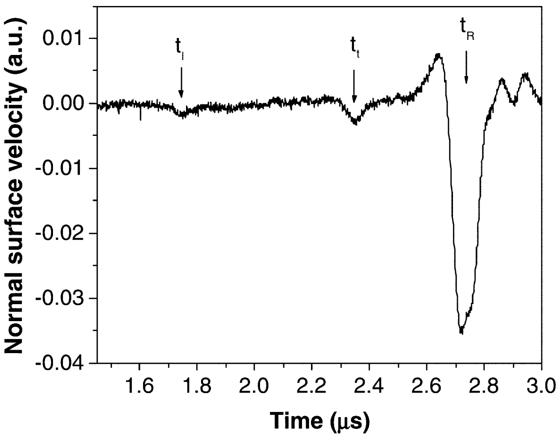

Fig. 3. Signal of surface waves observed for stainless steel. Arrivals of the longitudinal, shear and Rayleigh waves are indicated by vertical arrows.

5. Conclusion

High-amplitude surface waves were excited with nanosecond laser pulses through an absorbing liquid layer and detected with a probe-beam-deflection setup. Laser techniques enabled generation of very high-amplitude pulses with acoustic Mach numbers of approximately 0.01 that exhibit strong nonlinear effects during their propagation. Our measurements of SAW pulses in polycrystalline stainless steel have demonstrated that a compression of the pulse takes place in this material corresponding to a positive parameter of the local nonlinearity which was evaluated by fitting of the parameters of the evolution equation to the experimental data. The linear parameters needed for fitting were also evaluated from laser experiments: attenuation of SAWs was determined by measuring low amplitude pulses and the surface signals corresponding to arrivals of longitudinal and shear waves (precursors) were used for the determination of the bulk velocities and elastic moduli of the second order.

Acknowledgments

Support from NSF (grants 9870143 and 9970241) is gratefully acknowledged.

References

[1] A. Kolomenskii, A.A. Lomonosov, R. Kuschnereit, P. Hess, V.E. Gusev, Laser generation and detection of strongly nonlinear elastic surface pulses, Phys. Rev. Lett. 79 (1997) 1325–1328.

[2] A. Lomonosov, V.G. Mikhalevich, P. Hess, E.Yu. Knight, M.F. Hamilton, E.A. Zabolotskaya, Laser-generated nonlinear Rayleigh waves with shocks, J. Acoust. Soc. Am. 105 (1999) 2093–2096.

[3] A. Lomonosov, P. Hess, Effects of nonlinear elastic surface pulses in anisotropic silicon crystals, Phys. Rev. Lett. 83 (1999) 3876–3879.

[4] A.A. Kolomenskii, H.A. Schuessler, Characterization of isotropic solids with nonlinear surface acoustic wave pulses, Phys. Rev. B 63 (2001) 85413–85418.

[5] A.A. Kolomenskii, H.A. Schuessler, V.G. Mikhalevich, A.A. Maznev, Interaction of laser-generated surface acoustic pulses with fine particles: surface cleaning and adhesion studies, J. Appl. Phys. 84 (1998) 2404–2410.

[6] E.A. Zabolotskaya, Nonlinear propagation of plane and circular Rayleigh waves in isotropic solids, J. Acoust. Soc. Am. 91 (1992) 2569–2575.

[7] M.F. Hamilton, Yu.A. Il'inskii, E.A. Zabolotskaya, Nonlinear surface waves in crystals, J. Acoust. Soc. Am. 105 (1999) 639–651.

[8] V.E. Gusev, W. Lauriks, J. Thoen, Evolution equations for the Rayleigh waves in an isotropic solid, Phys. Rev. B 55 (1997) 9344–9347.

[9] V.E. Gusev, W. Lauriks, J. Thoen, New evolution equations for the nonlinear surface acoustic waves on an elastic solid of general anisotropy, J. Acoust. Soc. Am. 103 (1998) 3203–3215.

[10] A.L.A. Kolomenskii, A.A. Maznev, Surface responses in the laser irradiation of a solid: Rayleigh waves and precursors, Sov. Phys. Acoust. 36 (1990) 258–261.

[11] R.F.S. Hearmon, The third- and higher-order elastic constants, in: K.-H. Hellwege, A.M. Hellwege (Eds.), Landolt-Boernstein: Numerical Data and Functional Relationships in Science and Technology, vol. 11, Springer, Berlin/Heidelberg, 1979, p. 265, New Series, Group 3, Chapter 2.