Nonlinear surface acoustic wave pulses in solids: Laser excitation, propagation, interactions (invited)

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Laser techniques enabled generation of very high amplitude pulses with acoustic Mach numbers about 0.01. Such waves drive the medium into the nonlinear elastic regime and shock fronts can be formed during their propagation. As an intense surface acoustic wave (SAW) propagates, the temporal evolution of the wave shape provides information on the nonlinear acoustic parameters and the nonlinear elastic constants of the material. The nonlinear propagation of SAW pulses exhibits different types of nonlinear behavior depending on nonlinear acoustic constants. Changes of a SAW pulse shape were calculated using a nonlinear evolution equation. 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 the parameters of the evolution equation to the experimental data. Numerical simulations of a dispersive propagation of nonlinear SAWs in a system comprised of a substrate with a film were performed. A formation of a relatively stable portion of the waveform was found in agreement with recent observations of soliton-like SAW pulses.
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I. INTRODUCTION

Surface acoustic waves (SAWs) of high amplitude on a free surface of a solid (Rayleigh waves) possess several characteristic properties that are different from the bulk waves and attract special attention in view of practical applications in sensing and acoustoelectronics[1,2] and, on the global scale, due to their relation to seismic waves.[3] The particle movement in these waves has a longitudinal as well as transversal components. The energy of the waves is localized in the surface layer with thickness of about one wavelength and do not exhibit a dispersion in a homogeneous material, so that different harmonics can efficiently interact during the wave propagation.

Increase of the amplitude leads to a manifestation of nonlinear elastic properties of the material in the form of nonlinear distortions of the waveform, in particular enrichment of the high frequency domain occurs due to generation of higher harmonics. These processes were initially observed[4,5] and theoretically interpreted[6,7] for periodic waves. Recently, laser techniques for generation of nonlinear SAW pulses were developed resulting in the observation of strong nonlinear effects, such as the formation of shock fronts and drastic changes of the pulse shape and duration.[8–10] It was demonstrated[11,12] that a nonlinear compression as well as an extension of a SAW pulse may take place depending on the nonlinear acoustic parameters. For theoretical description of these phenomena a nonlinear evolution equation[13] was used. The theoretical studies were also extended to anisotromic materials and generalizations for this case were also derived.[14,15] A deposition of a thin film with elastic and mechanical properties different from those of the substrate gives rise to a dispersion.[16–18] It was found[19–21] that high-amplitude SAW pulses in such a layered system can exhibit a soliton-like behavior.

In this article the methods for studying nonlinear SAWs as well as experimental and numerical simulation results on the nonlinear SAW pulses are presented.

II. CONDITIONS NECESSARY FOR THE OBSERVATION OF THE NONLINEAR SAWS

There is an obvious distinction between the nonlinear process of SAW generation with pulsed laser radiation and the elastic nonlinearity that manifests itself in the propagation of a SAW pulse and is accompanied by an accumulation of nonlinear distortions, the latter being of primary interest in our consideration. Simple estimates indicate the range of stresses that should be reached for the observation of nonlinear effects in propagating SAWs. The magnitude of SAWs is conveniently described by a dimensionless acoustic Mach number $M = v/c_R$, where v is the amplitude of the surface velocity and c_R is the propagation velocity of the Rayleigh surface wave. Let us assume that the propagation length (which is limited by the size of the sample, attenuation length, or diffractional divergence of the wave) is of the same order as the nonlinear length, $L = b/\varepsilon M$, and equals 1 cm, where b is the acoustic wavelength and ε is the nonlinear acoustic parameter. Then for typical values for the laser excitation $b = 100$ μm (laser pulse duration is about $\tau = 20$ ns) and $\varepsilon \sim 1$ one obtains $M \sim 0.01$ and the necessary stress in the material in the generation region is $\sigma \approx \rho c_R{}^2 M/K \sim 1$ GPa (ρ is the density of the material that is assumed to be 2 g/cm^3) and the coefficient K describing the effectiveness of the SAW pulse generation by a stress normal to the surface can be

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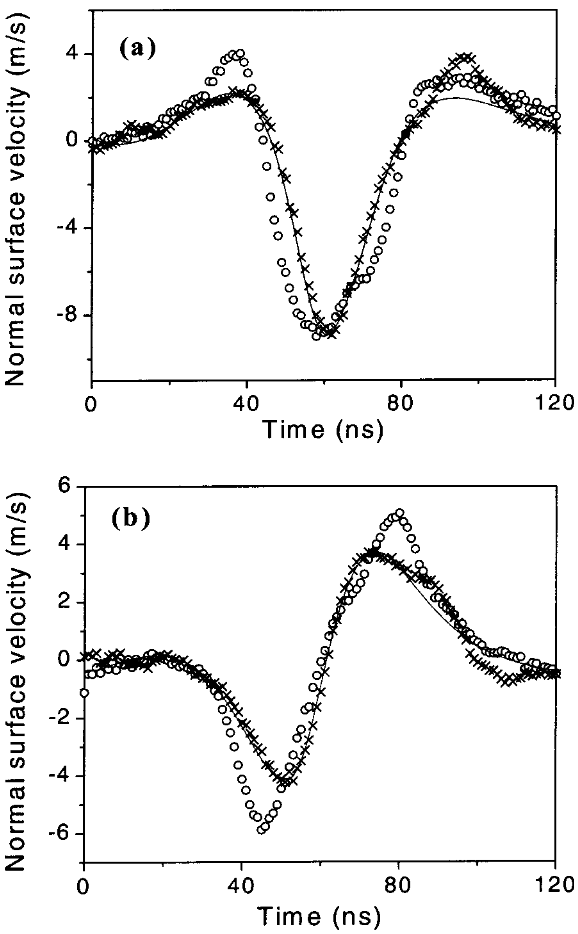

FIG. 1. SAW pulses registered at distances $x_1 = 5.2$ mm (open circles) and $x_2 = 16.2$ mm (crosses) from the excitation region; the calculated waveform is shown as a solid line: normal surface velocity (a) and the calculated waveform of the in-plane surface velocity.

assumed to be about 0.1.[22] Thermoelastic or direct ablation mechanisms usually cannot provide necessary high stresses; the first is limited by a relatively small thermal expansion coefficient and the second is limited due to the screening effect produced by the laser plasma.[23] However, in the interaction of laser pulses with strongly absorbing liquids[24] it was possible to reach these high stresses, and indeed a significant increase of the SAW pulse amplitude was observed when a layer of strongly absorbing liquid was imposed on the surface in the region of the interaction.[25]

III. 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,[7,14] and the other approach is based on the evolution equation[13,15] 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 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 also depend 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[15] contain elastic moduli of the second and third orders.

Taking into account attenuation and possible dispersion 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[13]

$$c_R^2 \frac{\partial \overline{v}(x,\omega)}{\partial x} = \frac{(-i\omega)}{4\pi} \int_{-\infty}^{+\infty} d\omega' \overline{v}(x,\omega') \overline{v}(x,\omega-\omega') \Big\{ \varepsilon_1 + \varepsilon_2 \Big[1 - \operatorname{sgn}(\omega')\operatorname{sgn}(\omega-\omega') + 2\varepsilon_3 \Big(\frac{\omega-\omega'}{\omega} \Big) \times [1 - \operatorname{sgn}(\omega)\operatorname{sgn}(\omega-\omega')] \Big\} - \alpha_0(\omega) c_R^2 \overline{v}(x,\omega) - i\omega D(\omega) \overline{v}(x,\omega), \qquad (1)$$

where $\overline{v}(x,\omega) = \int d\tau v(x,\tau)\exp(i\omega\tau)$ is the Fourier transform of the pulse profile, $\alpha(\omega)$ is the attenuation, and $D(\omega)$ describes the dispersion. Equation (1) was solved numerically.

IV. RESULTS AND DISCUSSION

Strong nonlinear effects in SAW pulses with laser generation were observed in several materials: fused quartz[8] and fused silica,[12] silicon,[9,10] polycrystalline metals (aluminum and copper[11,12]). A pulse stretching and formation of two sharp peaks in the vertical surface velocity and two corresponding shock fronts for the in-plane surface velocity were observed for fused silica that has a negative value of the parameter of the local nonlinearity ($\varepsilon_1 \approx -1$). In materials with negative ε_1, positive and negative peaks of the in-plane velocity waveform of a high-amplitude SAW pulse move away from each other and, consequently, two shock fronts, one in the head and another in the tail of the SAW pulse can be formed in this case.

A qualitatively different nonlinear behavior was observed in polycrystalline aluminum and copper. In these ma-

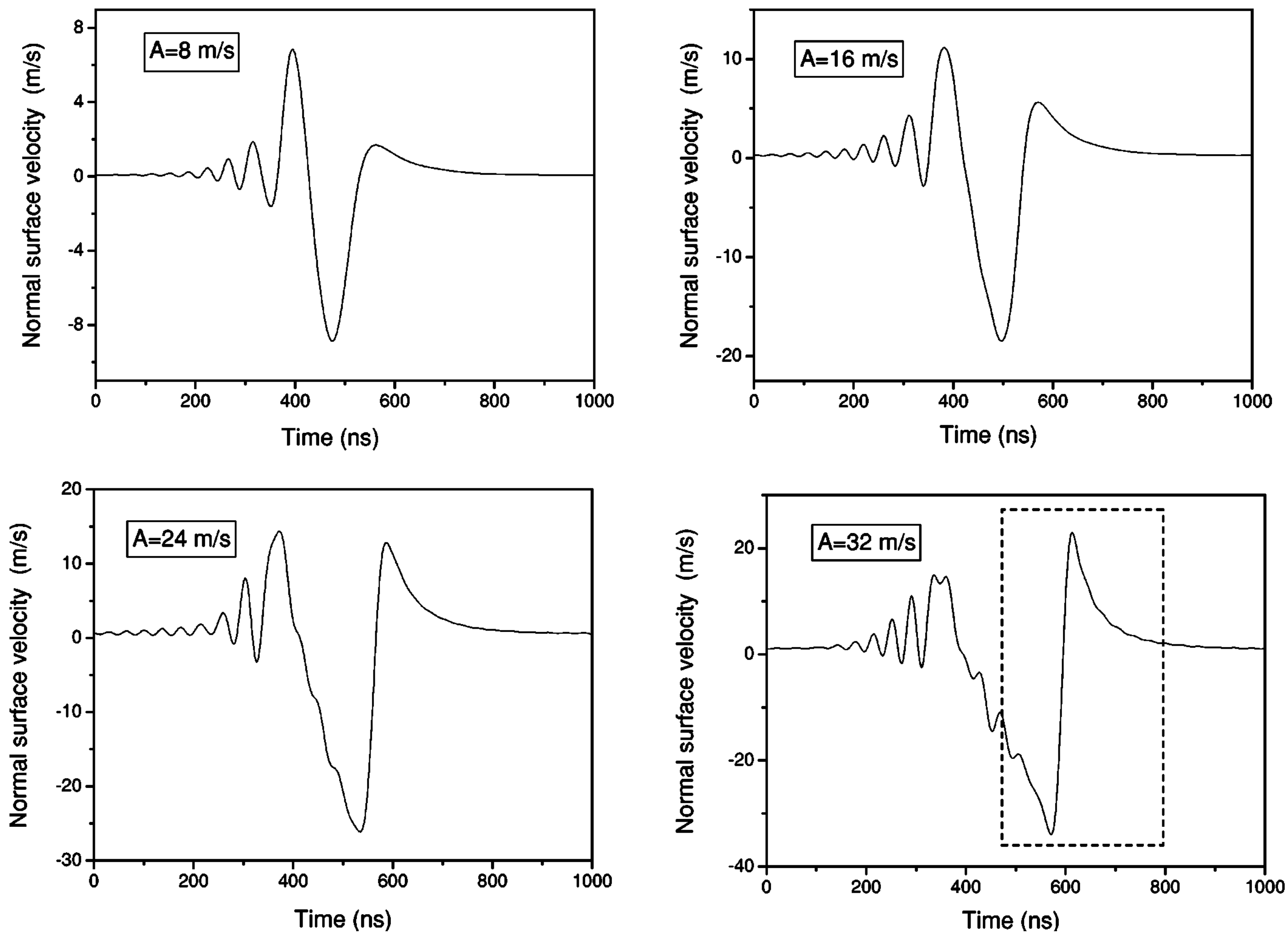

FIG. 2. Changes of the SAW pulse experiencing dispersion and nonlinearity calculated for increasing half peak-to-peak amplitudes (as indicated in the figures) at $x=40$ mm. The formed soliton-like portion of the pulse is indicated by a dashed box.

terials the parameter of the local nonlinearity is positive ($\varepsilon_1 \approx 1.0$ in polycrystalline copper and $\varepsilon_1 \approx 0.88$ in polycrystalline aluminum[11]) and a compression of the central part of the pulse takes place. It was concluded that the observed compression or extension of the SAW pulse mostly depends on the sign of the nonlinear acoustic constant determining the action of the local nonlinearity.[11]

Here we report measurements performed for polycrystalline (austenitic) stainless steel.[26] The pulses observed at two distances $x_1=3.6$ mm and $x_2=15.3$ mm are shown in Fig. 1. In this case also a compression of the SAW pulse was observed. It should be noted that in polycrystalline metals attenuation is rather strong in the MHz frequency range. This attenuation was determined by comparing spectral amplitudes of low amplitude SAW pulses at two propagation distances. The second order moduli were evaluated by measuring the propagation velocities of bulk waves from the signals of precursors.[27] The solid curve in Fig. 1 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 (the constant $D=0$ in this case) was performed for five measured pairs of pulses and the average values of the nonlinear acoustic constants were evaluated as $\varepsilon_1=6.0\pm1.7$, $\varepsilon_2=-(0.15\pm2.5)$, and $\varepsilon_3=-(3.0\pm1.5)$. The values calculated from the data on the third order elastic moduli[28] were found to be $\varepsilon_1=5.2$, $\varepsilon_2=-0.04$, and $\varepsilon_3=3.67$. The deviation of the experimental and theoretical values can be connected to individual variations of the material composition and a larger discrepancy for ε_3 can be due to the fact that the 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[7] a formation of a narrow negative peak in the normal surface velocity was also obtained.

We also performed simulations of the propagation of high-amplitude SAW pulses in a system consisting of a nonlinear substrate (we assumed $\varepsilon_1=-1$, $\varepsilon_2=-0.5$, $\varepsilon_3=0$, $c_R=3400$ m/s) with a thin film, so that the dispersion is linear $D(\omega)=D_0\omega$, $D_0=1.1\times10^{-7}$ $\mathrm{m\,s^{-1}\,Hz^{-1}}$, and $\alpha(\omega)=\alpha_0(2\pi)^{-2}\omega^2=\alpha_0 f^2$ (we assumed $\alpha_0=0.04$ $\mathrm{m^{-1}\,MHz^{-2}}$) is "classical" attenuation with quadratic frequency dependence.

In Fig. 2, SAW pulses with different initial amplitudes are shown after propagating a distance of $\Delta x=40$ mm in the case of an anomalous dispersion ($D_0>0$). At higher amplitudes a relatively stable soliton-like pulse is formed in the tail of the waveform. The increase of the wave amplitude creates a possibility that the dispersion and nonlinearity bal-

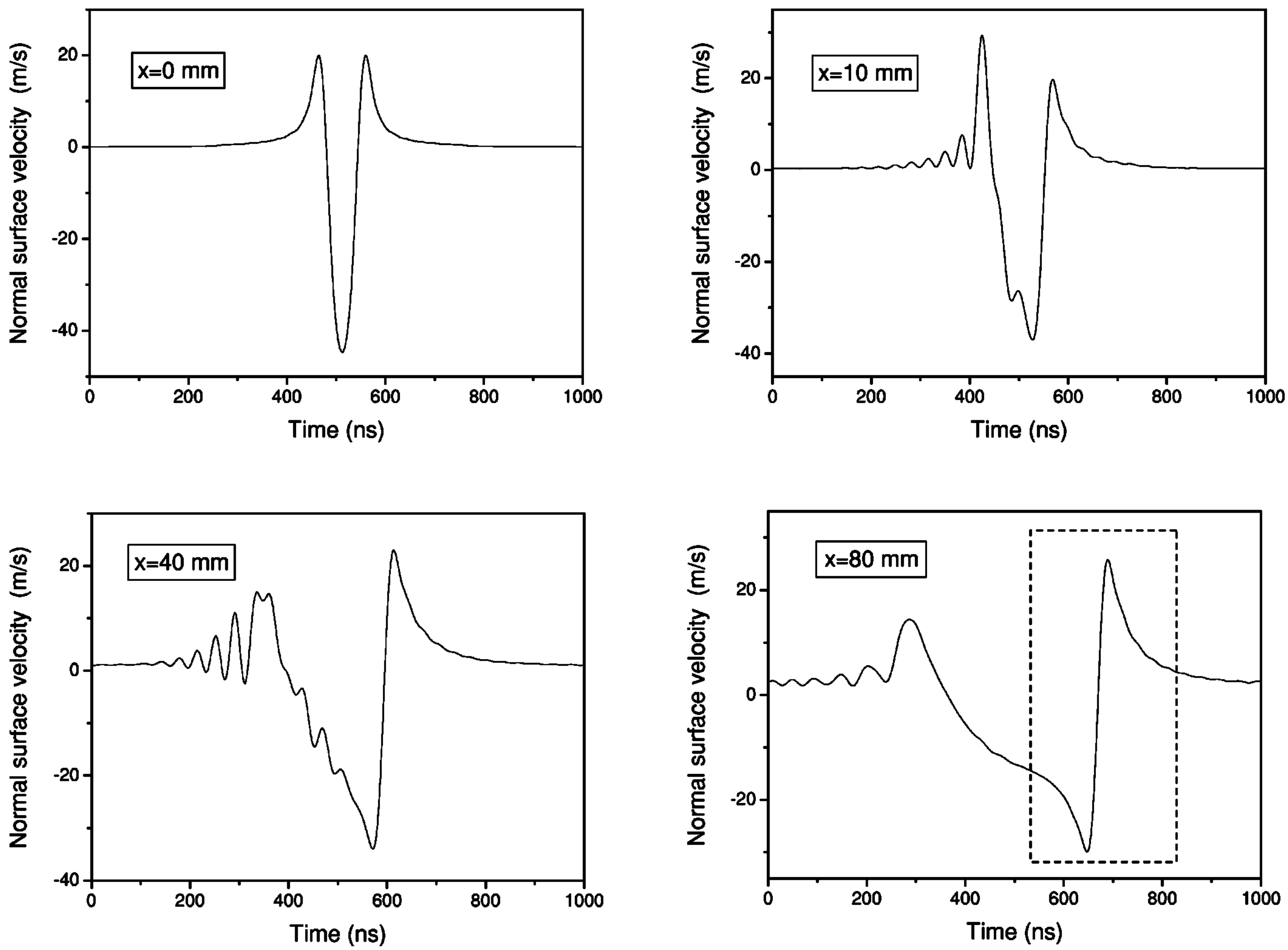

FIG. 3. Changes in the shape of the SAW pulse with the initial half peak-to-peak amplitude of 32 m/s at different propagation distances. The formed soliton-like portion of the pulse is indicated by a dashed box.

ance each other in such a manner that the formation of a relatively stable portion of the wave can occur. The waveforms of the pulse at different distances are shown in Fig. 3. The sequence of the plots shows how the soliton develops, for instance the changes in the tail part of the pulse at $x = 80$ mm compared to $x = 40$ mm are not as significant as in the beginning of the pulse propagation. It should be noted that the formation of a solitary wave in the tail of the pulse for an anomalous dispersion was calculated and observed in Ref. 21.

V. CONCLUSION

Laser-generated nonlinear SAW pulses are considered. Laser techniques enabled generation of very high-amplitude pulses with acoustic Mach numbers about 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 the parameters of the evolution equation to the experimental data. Numerical simulations with the nonlinear evolution equation, taking into account a nonzero dispersion, are qualitatively in good agreement with recent observations of soliton-like waves in a substrate with a covering thin film.

ACKNOWLEDGMENTS

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