Precursors in the optical excitation of giant surface acoustic wave pulses in solids

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The surface perturbations related to sound bulk waves are excited in a solid simultaneously with surface acoustic waves and propagate away from the source. These waves arrive before the arrival of the surface wave that gives the main contribution to the observed signal and therefore are referred to as precursors. In the wave zone the precursors can be registered at the surface as separate signals providing information on the elastic moduli of the material. We have observed the precursors for fused silica and stainless steel at relatively large distances due to extremely high pressure amplitudes created in the generation region. The parameters of the precursors were also calculated using a model of a normal force acting on a free solid surface. Relatively higher amplitudes observed in the experiments as compared to theoretical predictions are attributed to the effect of liquid loading during the generation process. [DOI: 10.1063/1.1512980]

I. INTRODUCTION

For an elastic half space with a free boundary a laser pulse produces simultaneously the excitation of surface acoustic waves (SAWs) as well as longitudinal and shear bulk waves. The surface perturbations produced by bulk waves propagate with higher velocities than SAWs and therefore play the role of precursors. In the far field the surface wave provides the main contribution to the oscillations observable at the surface of a solid, since precursors decay faster with propagation distance. However, in close proximity of the source the perturbations of the surface due to arrivals of bulk acoustic modes become comparable to those created by the surface wave. Precursors were observed in experiments,[1,2] but relatively little attention was paid to their theoretical description and experimental studies. For the calculation of the surface perturbations related to the precursors one needs to consider exact Green functions[3] or take into account peculiarities in the complex frequency plane, such as branch points,[4] when a Fourier transform is used for the derivation of analytical expressions. We estimate the accuracy of the measurements of the bulk sound wave velocities and consequently of the elastic moduli of solid materials with precursors and present experimental results and numerical simulations for different materials.

II. EXPERIMENTAL SETUP

In the present study, two *Q*-switched Nd:yttrium–aluminum–garnet lasers were used, one with a pulse energy of up to 100 mJ and duration of 26 ns and another with a pulse energy of up to 1.5 J and duration of 8 ns. The wavelength of 1.06 μm was employed in the excitation process. Samples had a thickness of 3–4 mm, which was sufficient for observation of the pure surface Rayleigh mode for all high frequencies of interest (>1 MHz). For the generation of SAWs with a straight front, the laser pulse was sharply focused with a cylindrical lens to a strip with a length ~10 mm and a width ~10 μm. In order to maximize the conversion of the laser pulse energy into mechanical energy, a thin (about 100 μm) strongly absorbing layer of carbon suspension in water was deposited in the area of the laser irradiation spot on the surface that was in addition covered by a glass plate.

The probe-beam-deflection technique was used for the detection of nonlinear SAWs. The measured signal was proportional to the normal component of the surface velocity. In the detection setup, the initial beam of the probe laser (Spectra Physics cw diode-pumped solid-state laser "Millenia" with an output power of up to 5 W) was split into two subbeams. The subbeams were focused onto the sample surface to form two probe spots of about 8 μm in size. This allowed us to probe the SAW pulse shape with nanosecond resolution in a small portion of the wave front. The SAW pulse signal was registered in a digital oscilloscope Tektronix TDS 680 C (1 GHz real-time bandwidth). The upper limit for the power of the probe beam was adjusted for each sample according to its reflectivity and set to avoid saturation of the photodiodes and the melting at the sample surface.

III. THEORETICAL MODEL

We characterize the mechanical action of the laser pulse absorbed in a thin surface layer and causing explosive evaporation as a short pressure pulse

$$p(\mathbf{r},t)=p_0 g(x)\exp(-t^2/\tau^2), \tag{1}$$

exerting a force normal to the surface of the solid, where p_0 is the pressure magnitude, $g(x)$ is the spatial distribution function, and τ is the duration of the pulse.

Taking into account the normal force of Eq. (1) in the boundary conditions and solving the wave equation by performing Fourier transform over spatial and temporal variables[4] we obtain for the normal surface velocity of the

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Rayleigh wave, corresponding to the contribution of a pole in the integration in the complex frequency ω plane,

$$\nu(\mathbf{r},t)=\frac{c_R}{4}\frac{ac_R\tau_0}{b^2}\frac{F_0}{\rho c_t^2}\Gamma\gamma\int_0^\infty k\exp(-k^2/4)\cos(k\xi)dk, \tag{2}$$

where the constants are presented by the expressions

$$\Gamma=[(1-\delta/2)[(1-\delta)^{-1}+(\delta_1-\delta)^{-1}]-2]^{-1},$$

$$\gamma=[(1-\delta/\delta_1)/(1-\delta)]^{1/4}.$$

Here $\delta=c_R^2/c_t^2$, $\delta_1=c_l^2/c_t^2$ and $c_{t,l,R}$ are the propagation velocities of the transversal (shear), longitudinal, and Rayleigh waves.

We approximated the one-dimensional spatial distribution as a Lorentzian with characteristic width a:$g(x)=a^2/(a^2+x^2)$. This approximation allowed us to obtain the following analytical expression for the Rayleigh wave:

$$\nu(\mathbf{r},t)=\frac{\pi^{1/2}}{8\pi}\frac{c_R^2\tau_p}{a\rho c_t^2}\Gamma\gamma Q(x,t);$$

$$Q(x,t)=\left(\frac{1-(x_+/a)}{1+(x_+/a)^2}+\frac{1-(x_-/a)}{1+(x_-/a)^2}\right), \tag{3}$$

where $x_\pm=x\pm c_Rt$. The precursor, corresponding to the contribution of the branch points ω/c_t, ω/c_l is described as

$$\nu_1(\mathbf{r},t)=\frac{\pi^{1/2}}{4\pi^2}\frac{\tau p_0}{\rho}\int_s^\infty d\alpha G(\alpha)Q(x,\alpha t), \tag{4}$$

where the explicit expression for the function $G(\alpha)$ is presented in Ref. 4. The integral in Eq. (4) differs appreciably from zero only for $\alpha\approx x/c_lt\approx 0$ and $\alpha\approx x/c_tt\approx 0$. These contributions correspond to the precursors with the arrival times near t_l and t_t.

IV. RESULTS

The precursors, which have much smaller amplitudes than the surface wave, were observed due to creation of high stresses (in the GPa range in the interaction region, which corresponds to the acoustic Mach number of about 0.01). The measurement of the propagation time of these waves over a known distance renders the propagation velocities of the bulk waves and enables the determination of the elastic moduli of the second order.

In Fig. 1 surface pulses in fused silica (Suprasil 1) are presented. One can see that the precursor of the longitudinal pulse that arrives first is positive. The precursor of the transversal wave is also positive. In this experiment the excitation was performed through a strongly absorbing layer of carbon suspension and can be modeled as a pressure pulse acting on the surface.

The precursors and the SAW pulse were calculated using Eqs. (2)–(4) and are shown in Fig. 2. The Rayleigh wave is normalized to $A_1=(\pi^{1/2}c_R^2\tau p\Gamma\gamma/8\pi a\rho c_t^2)$ and for the precursors the normalization to $A_2=(\pi^{1/2}\tau p_0/4\pi^2\rho x)$ is used. It should be noted that the normalization parameters $A_{1,2}$ have quite different values; for fused silica with $c_l=5940$ m/s, $c_t=3790$ m/s, $c_R=3420$ m/s, and $\rho=2.2$ g/cm^3, the normalization parameters are $A_1=6.9$ and $A_2=0.24$, when the other parameters were chosen close to the experimental values: $\tau=2\times10^{-8}$ s, $a=0.02$ cm, $x=0.5$ cm, and $p_0=3$ GPa. These values were also used in other simulations presented below. Due to difference in $A_{1,2}$, the relative magnitude of the precursors in Fig. 2 is increased by the factor $G=A_1/A_2=28$. The characteristic time scale (a/c_l) is shown in the graph with a horizontal bar.

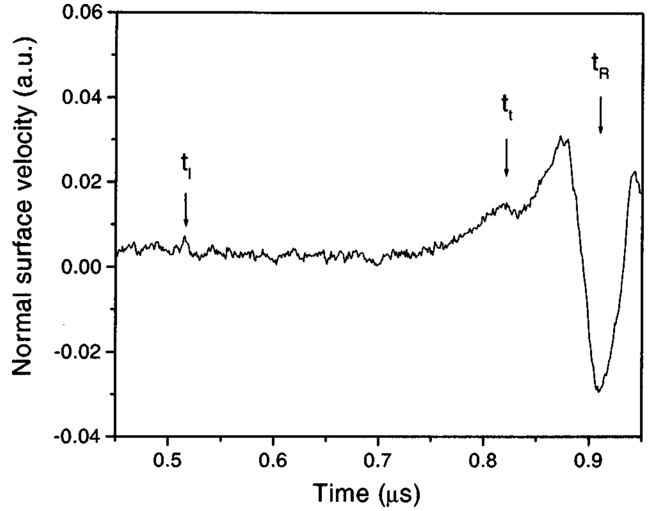

FIG. 1. Surface waves observed on fused silica. Arrivals of the longitudinal, shear, and Rayleigh waves are indicated by vertical arrows.

Qualitatively, the signals observed agree with the results of numerical simulations, however, for fused silica the experimental ratio of the amplitudes of the Rayleigh wave and the precursors is about a factor of 3 larger than what follows from the calculations. This can be explained by the influence of the liquid layer, which provides an increase of the magnitude of precursors relative to the excitation with a free surface.[5]

In Fig. 3 surface pulses observed in austentic stainless steel are shown. Since fused silica is a material with well

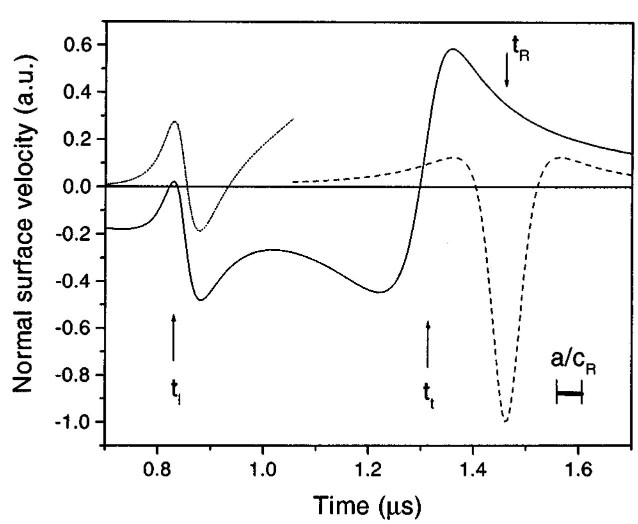

FIG. 2. Normalized wave forms calculated for fused silica. The precursor wave form is shown by a solid line, the Rayleigh wave is presented as a dashed line, and the sum of the initial portion of the Rayleigh wave and the precursor wave form is depicted as a dotted line. The dotted line has the same normalization as the precursor.

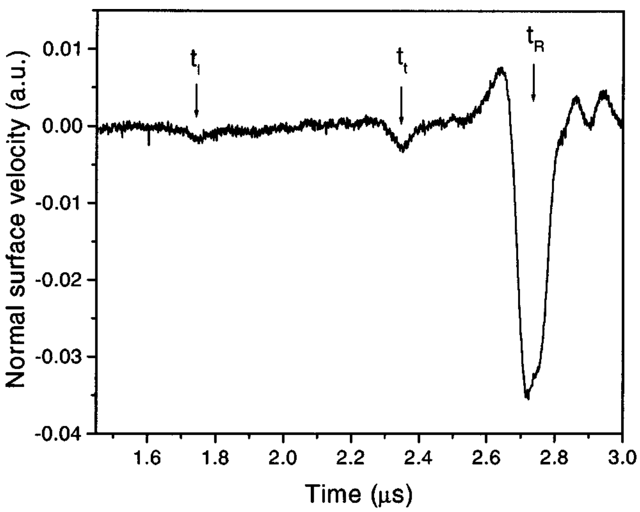

FIG. 3. Surface waves observed on stainless steel. Arrivals of the longitudinal, shear, and Rayleigh waves are indicated by vertical arrows.

defined elastic properties and the propagation velocities in it were determined with high accuracy, this material was used as a reference for the measurements of the propagation velocities in materials for which these velocities are not so well determined due to the variations in the composition. With this reference not only ratios of the velocities, but also the absolute values can be determined, using an independent measurement of the density. This method was implemented for the determination of the propagation velocities in stainless steel, for which the following parameters were evaluated: $c_l = 4500$ m/s, $c_t = 3300$ m/s, $c_R = 2900$ m/s, $\rho = 7.89$ g/cm^3, and consequently $A_1 = 2.6$, $A_2 = 0.068$, and $G = 38$. The ratio of the propagation velocities has a relative

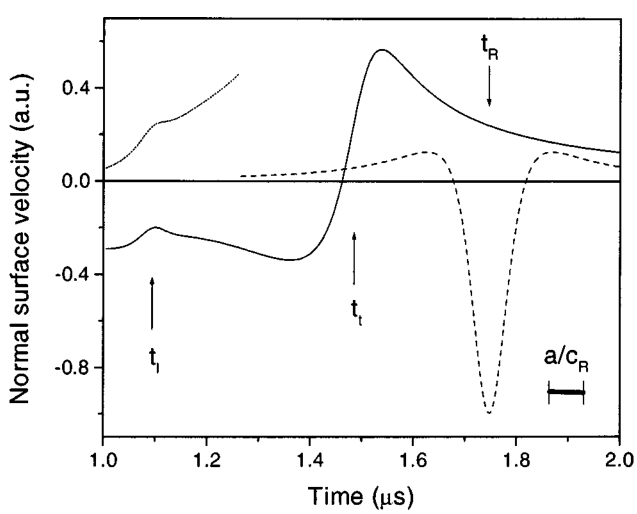

FIG. 4. Normalized wave forms calculated for stainless steel. The precursor wave form is shown by a solid line, the Rayleigh wave is presented as a dashed line, and the sum of the initial portion of the Rayleigh wave and the precursor wave form is depicted as a dotted line. The dotted line has the same normalization as the precursor.

error of about the ratio of the pulse duration to the propagation time, which was about 0.5% in this case. The result of the numerical simulation is depicted in Fig. 4. The precursor of the shear wave has the same sign in the simulation and the experiment. The experimental ratio of the amplitude of the precursor to the amplitude of the Rayleigh wave is about five times larger than the theoretical one. The deviation of the measured and calculated precursors of the longitudinal wave can be attributed to a change in the boundary conditions due to the loading of the surface with a liquid layer in the generation region.

The excitation through a solid absorption layer was also produced. In this case several reflections were observed. These signals corresponded to the reflected bulk longitudinal wave that propagated between the surface of the sample and the glass plate imposed on the absorption layer. These reflections were suppressed in the case of a liquid absorption layer, where only the signals of the precursors and the Rayleigh wave were registered. Therefore, this latter case is more favorable for a direct determination of the ratios of the propagation velocities.

V. CONCLUSION

High-amplitude surface waves were excited with nanosecond laser pulses through an absorbing liquid layer and detected with a probe-beam-deflection setup. The surface signals corresponding to arrivals of longitudinal, shear, and Rayleigh waves were studied experimentally and theoretically for fused silica and stainless steel. The longitudinal and shear waves are detected before the Rayleigh wave and play the role of precursors. The amplitude of the precursors decreases relatively quickly with the propagation distance and they can be detected mainly close to the source. The determination of the velocities of the bulk waves was possible with a relative error of about 0.5%. From these data elastic moduli of the second order can be evaluated. The isotropic model of a generation with a distributed pulsed normal force acting on a free surface was used for numerical simulations. A quantitative comparison of the calculated and measured precursors has shown that experimental amplitudes were several times higher, which can be explained by the influence of a liquid layer in the generation region that changes the boundary conditions.

ACKNOWLEDGMENT

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