Laser induced thermoelastic excitation of plane shear acoustic pulses

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Introduction

It is established theoretically[1-5] and is confirmed by multiple experiments[1,3,5-7] that when a pulsed focused laser radiation is absorbed near the surface of an elastically isotropic material, then the shear acoustic waves radiated at some angle to surface normal are not plane waves. Actually they are not generated by thermoelastic sources (induced by laser heating), but they are due to mode conversion of the longitudinal acoustic waves in reflection at mechanically free surface. Radiation of shear waves in normal direction is forbidden in isotropic material by symmetry considerations.
In order to subsequently apply shear acoustic beams inclined to the laser-irradiated surface for materials diagnostics the experiments should be conducted in specially designed geometry. However the inconvenience of signals with a rather large angular spectrum in comparison with the plane waves still remains. Another disadvantage is low efficiency of shear waves excitation when the diameter of the laser spot at the surface is large in comparison with acoustic wavelength. One more disadvantage (essential for wide-band spectroscopy) is the dependence of the duration of the shear pulses on the width of the laser spot, which in general leads to additional narrowing of their frequency spectrum in comparison with the plane longitudinal pulses emitted normally to the surface. It should be noted that these two latter disadvantages are closely related and, qualitatively speaking, are due to the fact that for thermoelastic excitation of shear waves in isotropic materials lateral gradients in laser energy density are necessary (and not just normal gradients as for the longitudinal waves).

In order to overcome the disadvantages mentioned above, the traditional method is to generate first plane longitudinal acoustic waves and then convert them into plane shear waves by mode conversion in oblique incidence on fluid-solid interface. Recently, picosecond plane shear acoustic pulses has been excited by mode conversion of picosecond plane longitudinal pulses in normal incidence on the interface of isotropic-anisotropic solids. Evident disadvantage of these methods is that only a part of the incident longitudinal wave energy is transformed into shear acoustic waves. In the present communication laser-induced thermoelastic excitation of plane quasi-transverse (QT) pulses near the surface of elastically anisotropic material is reported for the first time. It should be clearly stated that thermo-optical excitation of shear pulses in anisotropic media has been realised earlier. However, in these experiments laser irradiated surface of material was oriented normally to one of crystallographic symmetry axes. As a consequence of this particular geometry plane QT acoustic waves were not generated. The excited quasi-shear pulses were emitted at an angle to surface normal. In the experiment described bellow, the chosen orientation of the crystal surface relative to symmetry axis provides opportunity to excite plane QT acoustic pulses with wave vector normal to the surface, not via mode conversion but directly by bulk thermoelastic sources.

Theory

Efficiency of thermoelastic generation of QT plane waves in an anisotropic media depends on the orientation of the plane of excitation relative to the crystallographic axes. Thermoelastic generation was already studied in anisotropic media but the results presented concerned propagation on specific crystallographic directions. In order to determine the angle Θ , which provides maximum transverse particle motions in a crystal, we have to solve the problem of thermoelastic excitation on a plane surface in the 1D geometry. The basic equations of the model are: (i) the inhomogenous wave equation and (ii) the diffusion equation of heat. The conditions at the surface of excitation are: (i) condition of no stress on the surface and (ii) continuity of thermal flux density, as we assume surface heating (this assumption is valid for most metals irradiated by nanosecond laser pulses). In the general case, three plane waves with wave vector normal to the surface can be generated: one quasi-longitudinal (QL) and two quasi-transverse (QT1 and QT2). Polarization of the three waves are mutually orthogonal. The one dimensional problem is solved by using Fourier and Laplace transforms.
We studied the particular class of crystals of hexagonal symmetry (Zn, Te, …). In this particular class, only QT and QL waves with polarization in the plane containing the normal (x_3) and the C_6 crystal symmetry axis (sagittal plane), can be excited. The pure transverse wave (TA) cannot be excited by reason of symmetry. Moreover, the results depends only on the angle θ of the C_6 axis relative to the surface normal. The solution for the components u_2 (in-plane) and u_3 (out-of-plane) of the particle displacement can be written in the form : $u_i^{QT(QL)} = A_i^{QT(QL)} \cdot g(t - x_3 / v_{QT(QL)})$, with i = 2, 3, where $g(t)$ represents a normalised time profile of the acoustic pulses. For a zinc crystal, the calculated amplitudes A_2^{QT}, A_3^{QT}, A_2^{QL} and A_3^{QL} have been plotted versus the angle θ , using available data on the crystal parameters (figure

1). The plot shows the strong dependence of the transverse amplitude on θ for the QT wave which maximum efficiency of transverse motion is achieved for $\theta \approx 30°$.

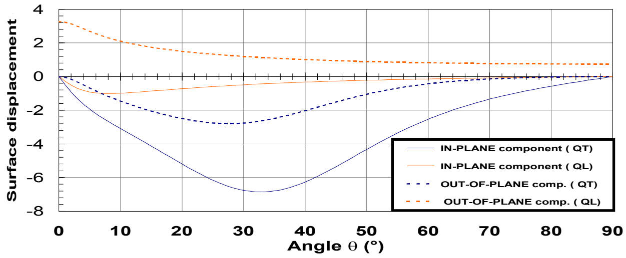

FIG. 1. Calculations of in-plane (u_2) and out-of-plane (u_3) components of the surface displacement generated by thermoelastic stress versus angle θ for QT and QL plane waves in zinc crystals.

Experiment

Thermoelastic excitation of the acoustic plane pulses was achieved in zinc single crystals by means of a Q-switched Nd:YAG laser at λ =1064nm, with 50ns pulse duration and 10Hz repetition rate. The zinc crystals were cylinders of 2mm in thickness and 10mm in diameter, with parallel and flat faces, unpolished on the surface of excitation (where acoustic sources are localised) and polished on the other face to achieve good light reflection. The incident multimode laser beam of 7mm in diameter was apertured to a 2mm spot before irradiating the sample, providing quasi uniform power density on the sample with a fluence in the range 100-200mJ/cm², which corresponds to the thermoelastic regime.[5] The out-of-plane component of QT can be detected by means of an out-of-plane sensitive interferometer.[1] The out-of-plane component (u_3) of the surface displacement at epicentre (at the rear surface) has been measured. The probe beam of the interferometer was an unfocused He-Ne beam of 0,8 mm in diameter reflected normally at epicenter. The ultrasonic signal received by a photodetector of 100MHz band-pass was visualised on a storage oscilloscope triggered by a silicon photodiode receiving scattered light at 1064 nm.

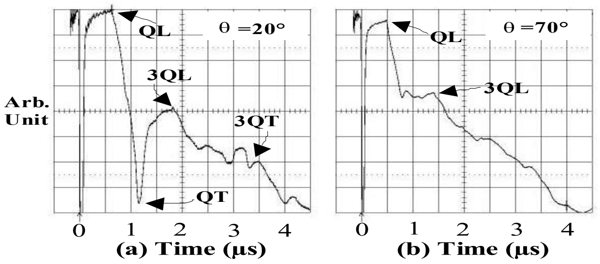

FIG. 2. Measured out-of-plane component of surface displacement in epicenter for two zinc crystal cuts: (a) θ=20° and (b) θ=70°.

Figure 2 show the results with two zinc samples. The calculated time derivative of the QT or QL displacement signals (proportional to the out-of-plane component of surface velocity) gives sharp echos of 50 ns duration. The time of flight between the echos serves to calculate phase velocities of the QL and QT waves, which are in good agreement with the calculated velocities from elastic constants. Although the out-of-plane interferometer gives a demonstration that excitation of the QT pulses has been realised, we have no information about the transverse motion of the surface. For this reason we have detected the shear strain induced by the QT pulse in an isotropic medium by means of an optical setup similar to that used in photoelasticimetry.

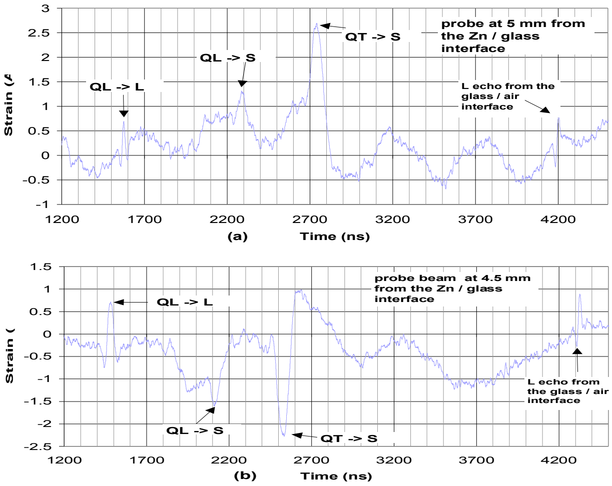

Figure 3 (a) and 3 (b): Strain pulses detected in a glass cube with photoelasticimetric setup. These signals were obtained when the sagittal plane of zinc crystal (θ= 20°) is perpendicular to the probe beam. The signals correspond to two orientations of the zinc crystal differing by 180° around the crystal normal.

The zinc crystal was coupled to a glass cube. The QT and the QL pulses arriving at the Zn/glass interface are converted in pure shear (S) and longitudinal (L) pulses which propagate in glass at different velocities (v_S =2830m/s and v_L=4720 m/s). The strain induced by the acoustic pulses is detected with a He-Ne probe beam propagating perpendicularly to the direction of propagation of the acoustic pulses. The probe is focused to a spot of 30µm in diameter, small enough to achieve good spatial resolution of a shear pulse of 50ns duration. The signals are shown on Figure 3a and 3b. The time of flight of the different acoustic signals serve to distinguish L and S pulses. Mode conversion from QT to S pulse and from QL to S and L pulses are observed. After rotation of the zinc crystal of 180° around the surface normal, the sign of the shear pulses changes, whereas the sign of L pulses remains unchanged.

Conclusion

A simple 1D model of thermoelastic excitation demonstrate that *plane* quasi-transverse acoustic pulses in an anisotropic absorbing medium can be directly excited by the thermoelastic process. Experiment performed with a zinc crystal confirms this prediction. This method of excitation could be applied to generate picosecond shear waves pulses by means of femtosecond laser. Application of laser induced shear pulses could then be used for diagnostic of fluids in picosecond acoustic or wide-band spectroscopy of condensed media.

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