Amplification of the surface elastic wave in a solid tracked by a laser beam

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The predicted [A. M. Dykhne and B. P. Rysev, Poverkhnost', fizika, khimiya, mekhanika, No. 6, 33 (1983)] linear, resonant growth in the amplitude of a surface elastic wave in a solid excited by the absorption of laser radiation, scanned at the velocity of surface waves, focused on the surface is observed experimentally. The dependence of the amplitude of the surface wave on the scanning velocity, the dependence of the amplitude at resonance and the width of the resonance curve on the scanning length and intensity of the radiation are obtained. The results presented agree well with the theory.

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The theoretically predicted excitation of a surface elastic wave by the thermal action of laser radiation focused on the surface of a solid and scanned at the velocity of surface waves is observed experimentally for the first time. The process, resonant in nature with respect to the velocity, grows linearly in amplitude at resonance as a function of time.

1. The use of a moving focal point of laser radiation as a local source of heat permits exciting elastic waves in a liquid via thermoelasticity.[1] Excitation of surface elastic waves of large amplitude in solids in an analogous manner was proposed in Ref. 2.

In this paper, we present theoretical estimates and report the first results of the experimental study of this effect.

Let a focal spot of laser radiation (in the form of a strip stretching across the direction of motion) be scanned along the surface of an opaque solid at a velocity close to the velocity of propagation of surface elastic waves U. The energy of the light is absorbed in a thin layer of matter, which leads to local heating of the region near the surface beneath the spot. Thermoelastic deformation arises here and the deformed region moves along the surface with velocity U. If the source accompanies the wave, then thermoelastic deformation, caused by the source at a given time, is superimposed in phase on this moving deformation. As a result, the deformation undergoes linear, resonant growth with time.

It is interesting to note that although the deformation is thermal in nature, the substance may be heated insignificantly and the deformation may exceed many-fold the quantity αT (α is the coefficient of thermal expansion). This is related to the fact that a large deformation can be built up with distance with relatively small local heating.

The problem of the excitation of a surface wave, using the proposed method, consists of solving the equation of motion of the elastic medium, which includes thermoelasticity, together with the equation of heat conduction, which contains the moving source.[2] The following expression was obtained for the relative change in volume accompanying the deformation of the medium in the wave on the surface itself for the case when the velocities of the source and of the wave are exactly at resonance:

$$b\,\frac{\alpha I}{\rho C a}\,t\;,$$

where I is the absorbed radiation intensity, a is the width of the focal strip, ρ is the density, C is the specific heat of the medium, t is the time, and b is a constant whose value is determined by the elastic properties of the medium.

2. In the experiments, we used a CO_2 laser with constant generation throughout the pulse and with intensity up to 10 kW.[3] The laser radiation was focused onto a strip of length $l = 10$ mm and width $a = 1$ mm, which, with the help of a rotating mirror, moved along the surface of a bulk ($5\times10\times30$ cm) sample of duraluminum. The scanning velocity varied with the angular velocity of rotation of the mirror. The absolute error in the velocity measurements did not exceed 1% and the relative error did not exceed 0.3%. The scanning length L was varied with movable screens. The radiation power W was decreased with the help of attenuators. The surface wave was recorded with a TsDS-16 meter glued onto a v-transducer,[4] which was placed at the end of the scanning path. The same meters were placed on adjacent and opposite faces of the specimen in order to record the background waves.

3. The experimental results are shown in Figs. 1 and 2. The amplitude of the wave, measured at the end of the scanning segment L (3–17 cm) depended in a resonant manner on the scanning velocity. The magnitude of the resonant velocity was $v_p = (2.94 \pm 0.03)\times 10^3$ m/s, consistent with the velocities of surface elastic waves for

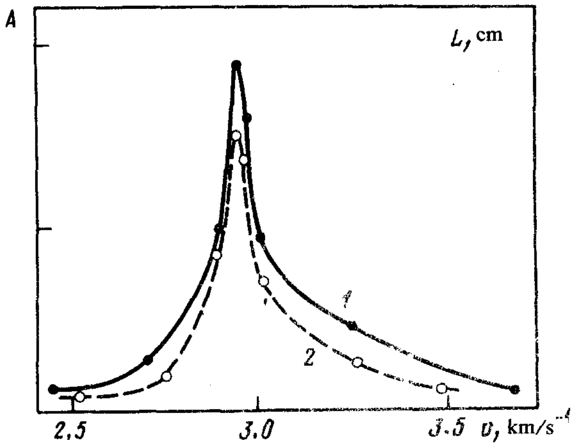

FIG. 1. Dependence of the amplitude of the wave (in relative units) at the end of the scanning path on the velocity of the focus.

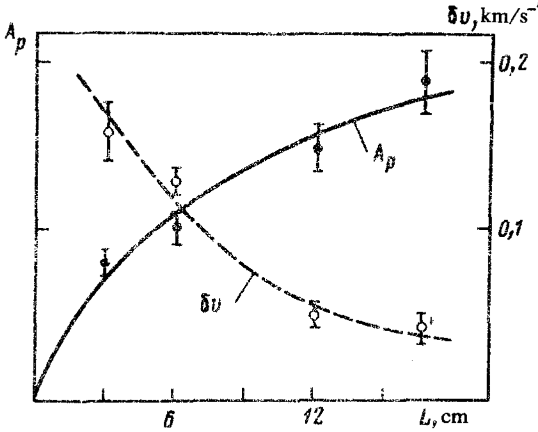

FIG. 2. Dependence of A_p, the amplitude of the wave at resonance (relative units), and δv, the half-width of the resonance, on the length of the scanning path.

duraluminum[4]: $U = (2.86\text{–}2.93)\times 10^3$ m/sec. The dependence of the amplitude of the wave at resonance on the length of the path L is shown in Fig. 2 (solid curve).

We can draw some conclusions from the following facts: 1) v_p is known to be lower than the velocities of volume waves, the transverse velocity $c_t = 3.1\times 10^3$ m/s and the longitudinal velocity $c_l > \sqrt{2}c_t$, 2) the increasing dependence of the amplitude on L, whose resonance occurs precisely at the velocity $v_p = U$, and 3) the background sensors did not record the considerable regular signal. We conclude, therefore, that the excitation of a surface elastic wave was observed in the experiments.

The deviation of the dependence $A_p(L)$ from a linear dependence is probably related to the diffraction spreading of the quasiplanar wave with aperture l, which corresponds qualitatively to the function $\sim L\,[1 + L^2(2a/l^2)^2]^{-1/2}$.

The fact that the resonance has a width (Fig. 1) is a result of the finiteness of the longitudinal dimensions of the source a and of the deformed region ($\sim a$). As a result, the amplitude should increase in the presence of detuning of the velocities Δv, but only until the wave and the source are separated by a distance of the order of a. Thus, amplification is guaranteed by the condition $\Delta v/U \sim a/L$. Accordingly, we estimated the size of the deformed region from Fig. 1 and from the dependence of the width of the resonance δv on L (Fig. 2), 1–3 mm, i.e., it is of the order of a, as it should be.

The dependence of the amplitude of the wave at resonance on the intensity of the radiation W was also investigated. At $W = 0.5\text{–}7.0$ kW, the amplitude increased linearly with increasing intensity, which indicates the elastic nature of the deformations that arise. The magnitude of the maximum displacement of the surface was estimated from data on the sensitivity of the TsDS-16 sensor: $\approx 0.1\ \mu$m. A displacement of the same order of magnitude is also obtained using the equation in Ref. 2. The estimated heating of the surface was ≈ 3 K.

As the calculations in Ref. 2 show, an increase in I by approximately two orders of magnitude and optimization of the remaining parameters permits approaching the region of nonlinear deformations. Excitation of such waves would make it possible to subject the layer of the solid near the surface to considerable deformation, without affecting the bulk of the specimen. This method of excitation could be used for mechanical working of the surface (we note that it is a contact-free method) and for discovering surface defects, and it will also permit studying nonlinear surface waves.

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