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Surface-acoustic-wave generation by thermoelasticity

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Short laser pulses were used for generating surface acoustic waves (SAWS) on aluminium via the thermoelastic effect. There exists a simple relation between the temporal and spatial pulse width at which the SAWS exhibit maximal amplitude.

INTRODUCTION

The use of surface acoustic waves (SAWS) in non-destructive testing plays an important role. In certain cases it is desirable to apply a non-contact technique for generation and detection of SAWS because the specimen may have to be tested at elevated temperatures or may not directly be accessible. For generation, such a technique is the thermoelastic source with single frequency-modulated laser beams as in photoacoustic imaging or pulsed laser sources as in remote NDE. For the latter, this has been demonstrated previously by Lee & White (1968) and by Aindow *et al.* (1981). However, no systematic studies have been performed on the conditions required for maximal efficiency or lowest 'insertion loss'. In this paper we report on this topic.

EXPERIMENTAL RESULTS

We generated SAWS on a polycrystalline aluminium sample by using a pulsed ruby laser, the pulse width of which was 50 ns (full width at 1/e points of the intensity-profile of Gaussian shape $I = I_0 \exp(-t^2/\tau^2)$). The laser beam was focused either to a spot by a circular lens or to a line by a cylindrical lens. We used the laser only in the TEM_{00} mode in order to assure a well-defined spatial Gaussian profile $I = I_0 \exp(-r^2/a^2)$ during the course of our measurement. The optical intensity was kept below 1 MW cm^{-2}, so that the data were only taken in the thermoelastic régime. The received signals were detected by a wedge transducer, the centre frequency of which was 10 MHz, and exhibited a 6 dB bandwidth of 6 MHz. The transducer was located *ca.* 1 cm from the laser spot or line. In the case of the line source, we first expanded the laser beam perpendicular to its axis in order to obtain negligible optical-intensity variation over the width of the transducer. A schematic representation of our experimental arrangement is shown in figure 1.

Figure 2 shows a typical experimental result for the intensity of the SAW as a function of the full-width $d = 2a$ of the laser spot or line. As can be seen very clearly, there is a pronounced maximum at a certain diameter d or width $2a_{\max}$ of the laser spot source (solid line) or line source (dashed line), respectively. A quantitative measure of the intensity of the SAW was obtained by integrating, with respect to time, the squared amplitudes, u^2, of the received signals rather than by measuring peak values. This procedure was chosen because the signals were strongly amplitude-modulated in particular for $a \neq a_{\max}$ (Arnold *et al.* 1985).

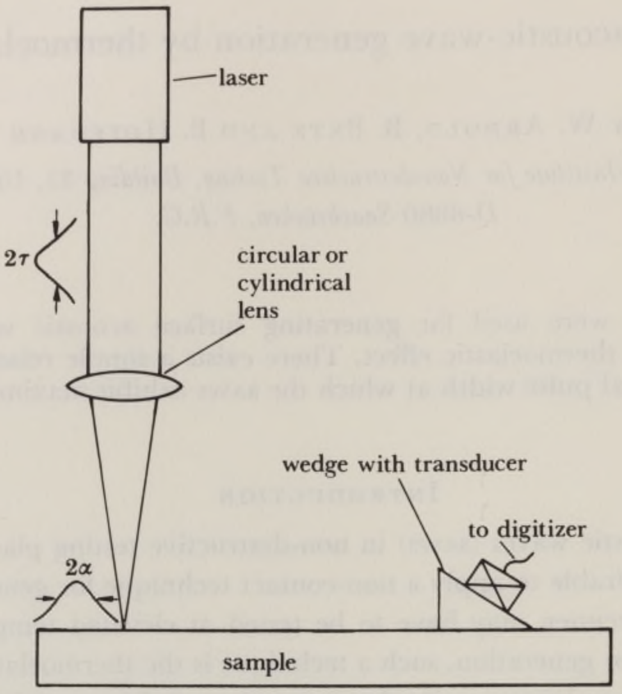

FIGURE 1. Principle of measurement. The sample was made out of polycrystalline aluminium.

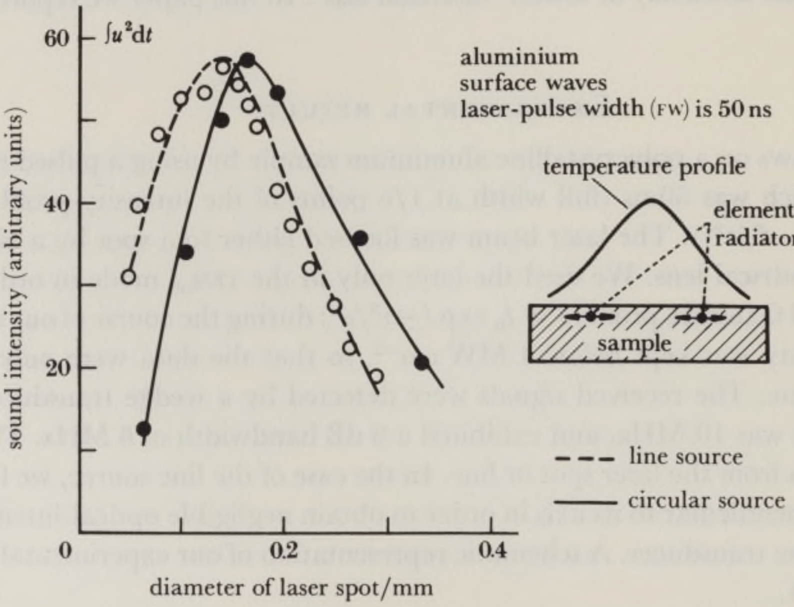

FIGURE 2. Surface-wave intensity as a function of laser-spot diameter. There is a pronounced maximum which occurs when $a = v_R \tau$ (here $v_R = 2.9 \cdot 10^3$ m s^{-1}, $\tau = 25$ ns, $2a_{max} = 0.16$ mm ($\pm 10\,\%$)). The insert shows schematically that each radial component contributes to the measured signal. Note that there is also a temperature gradient normal to the surface contributing to SAW generation because this type of wave contains longitudinal as well as transverse components.

Discussion

The observed behaviour can be understood in a qualitative manner quite easily. One should keep in mind that the gradient of the temperature is at the origin for sound generation (White 1963). When d is large, the lateral gradient of the temperature profile is small, and hence the efficiency of SAW generation. In the limit of a lateral infinite laser-pulse profile only longitudinal waves are produced because there is then only an axial gradient of the temperature due to thermal diffusion within the timescale of the laser pulse. When d is small, however, the efficiency is small because a point or very thin line source is obtained, the extent of which is small compared with the wavelengths produced. It is obvious that there should exist a certain diameter or width $2a$ of the laser-pulse profile, allowing mostly constructive interference of the individual SAW components produced at each expanding surface element. From these arguments, maximal efficiency should occur if

$$d = 2\tau v_\mathrm{R} \tag{1}$$

holds. Here, v_R is the Rayleigh velocity and 2τ is the laser-pulse width. Inserting into (1) $v_\mathrm{R} = 2.9 \times 10^3\ \mathrm{m\ s^{-1}}$, which holds for aluminium and $2\tau = 50$ ns, we obtain for $d = 2a_\mathrm{max} = 0.145$ mm, which agrees very well with our experimental results.

Our findings can also be understood more quantitatively. We know of two theoretical considerations relevant to the problem. In both, the radiant power is assumed to be modulated at a single frequency $\omega/2\pi$, whereas the lateral, spatial profile of the radiating beam was assumed to be rectangular of width d (Lee & White 1968) or Gaussian of full-width $2a$, corresponding to our experimental situation (Krylov & Pavlov 1982). In the first case maximal efficiency should occur if $k_\mathrm{R} = \pi/2d$, and in the second case for $k_\mathrm{R} = \sqrt{2}/a = \sqrt{8}/d$. Here, k_R is the wavevector of the SAW. It is reassuring that both calculations give quite similar results. However, we generated a spectrum of SAWs due to the finite optical pulse width. This can be incorporated into the theory of Krylov & Pavlov (1982) in a simple way. These authors have calculated the potentials ϕ and ψ of the SAW from which its displacements can easily be derived. When multiplying the potentials with the Fourier transform of the temporal laser-profile, we get the displacements for each frequency component of the optical intensity profile. It is then straightforward to calculate the maximal efficiency as a function of the parameters a and τ because the SAW intensity is proportional to the prefactor squared of the potentials (Seshadri 1983). As a final result one obtains (1) (Arnold *et al.* 1985).

We should like to thank K. J. Langenberg for helpful discussions.

References

Aindow, A. M., Dewhurst, R. J., Hutchins, D. A. & Palmer, S. B. 1981 *J. acoust. Soc. Am.* **69**, 449.
Arnold, W., Betz, B. & Hoffmann, B. 1985 *Appl. Phys. Lett.* **47**, 672.
Krylov, V. V. & Pavlov, V. I. 1982 *Soviet Phys. Acoust.* **28**, 493.
Lee, R. E. & White, R. M. 1968 *Appl. Phys. Lett.* **12**, 12.
Seshadri, S. R. 1983 *J. appl. Phys.* **54**, 1699.
White, R. M. 1963 *J. appl. Phys.* **34**, 3559.

Discussion

R. J. Dewhurst (*Department of Applied Physics, University of Hull, U.K.*). I suggest another reason why the Rayleigh-pulse amplitude decreases with small laser spot size: as the width of the laser spot decreases, so does the width of the Rayleigh pulse which is dipolar in nature. As the propugates beneath the transducer, the transducer measures a signal which is a convolution of the Rayleigh-pulse waveform with the response time of the detection system. Our own experience suggests Dr Arnold may be in this régime for small spot sizes; some time convolution of a short dipolar pulse will lead to a signal with decreased amplitude, as shown in his results.

W. Arnold. I agree that there is some distortion of the shape of our measured curve 'intensity of the SAW against spot/line width' due the response time of the detection system. However, if this were the only reason for the observed maximum, it should occur at approximately 0.3 mm because this corresponds to the maximal sensitivity of the wedge transducer (as measured in wavelengths on aluminium) a factor of two larger than the experimental one. I think that the maximum we observed is caused because of optimal matching of the spatial and temporal frequencies of the power spectrum of the laser pulse.

R. B. Thompson (*Ames Laboratory, Iowa State University, Ames, Iowa, U.S.A.*). For the line source, the signals that Dr Arnold observed would be likely to have depended on the length of the line. What was this length and how did it affect the data?

W. Arnold. The length of the line was typically 3 cm, whereas the width of the wedge transducer was 0.5 cm. It was assured that the optical power did not vary more than 10% over the width of the transducer. In addition, the data were taken at various optical-power densities, from which we verified the linear power dependence of the ultrasonic amplitude optical power as it is expected in the thermoelastic régime. However, the data were plotted for *one* single power density at *all* line widths so that the data did not depend on the length of the line. There might be some diffraction due to the finite length, but we did not measure this. I refer to Aindow *et al.* (1982) in which this point is discussed. They showed that the line source exhibits a high degree of directivity perpendicular to its length.

Reference

Aindow, A. M., Dewhurst, R. J. & Palmer, S. B. 1982 *Optics Commun.* **42**, 116.

R. E. Green (*Center for Nondestructive Evaluation, The Johns Hopkins University, Baltimore, Maryland, U.S.A.*). I report on a technique developed by Professor J. Wagner, one of my colleagues at The Johns Hopkins University, who has used a triple-exposure, dual-reference-beam holographic technique and heterodyne analysis for full-field recording and measurement of surface acoustic wave displacements, generated by laser beam, as small as 9 Å. To the best of my knowledge, this is the first time that such full-field images of laser-generated, propagating, surface-acoustic waves have been obtained with a displacement sensitivity approaching that obtainable with a point-detector, optical interferometric probe.

W. Arnold. I thank R. E. Green for his comment.