Studies of Laser-Driven Shock Waves in Aluminum

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We have observed the structure and velocity of laser-driven shock waves in aluminum foils. We have measured shock velocities as high as 13 km/s and shock luminosity rise-times less than 50 ps, and we have inferred pressures of 200 GPa and shock-front thicknesses < 0.7 μm. These results suggest that such techniques may be used for measuring equation-of-state parameters and studying the detailed structure of shock fronts.

The development of high-power pulsed lasers and high-sensitivity, ultrafast streak cameras has opened possibilities for studying hydrodynamic phenomena in a pressure and temperature regime previously obtainable only with nuclear explosives. We have initiated a research program exploiting these new tools for investigation of temporal and spatial shock structure and measurement of equation-of-state (EOS) parameters. In this Letter we report the results of experiments in which, for the first time, laser-driven shock waves are observed by their own luminosity. We include measurements of shock velocity, shock risetime and luminosity structure, and material motion.

Several experimenters have used high-energy lasers to measure EOS parameters. Van Kessel and Sigel[1,2] observed shock waves traveling through thick, transparent samples by directing a second laser through the sample onto a camera, and they were able to deduce pressures, densities, and temperatures behind the shock front. Billon *et al.*[3] photographed target blowoff with a second laser and deduced an average shock velocity in the target by neglecting the shock-formation time and assuming that the shock traversed the entire thickness of the foil. For thin, opaque targets, where we cannot use another laser to sidelight the shock front, we chose to measure the arrival of the shock at the target surface by observing the shock luminosity at two depths in a target made with a thin evaporated layer covering half of the shock area.

Figure 1 shows a schematic of the target. The laser energy is initially deposited near the surface of the foil (solid circle) where it generates hot electrons which in turn redeposit some of the energy throughout the nearby volume (dashed line). The sudden heating causes a shock wave to propagate through the target. If the temperature behind the shock front is high enough, we can observe the shock emergence first at the back of the substrate and later from the added layer.[4] It is important that the substrate be thicker than the range of the fast electrons to minimize preheating, but it must also be thin enough to prevent a rarefaction from overtaking the shock before its emergence. Measurements by Giovanielli[5] show that 90% of the hot electrons from laser pulses similar to ours are stopped by 8 μm of aluminum. For our experiments the substrate was 13 μm thick and the evaporated layer ranged in thickness from 2 to 5 μm. We also studied some targets without steps to learn about the time history of the light from them.

The 1.06-μm neodymium-glass laser delivered from 20 to 40 J in 300 ps to the target inside a 1-m-diam vacuum chamber. The laser light struck the target in an $f/3.5$ cone. By moving the target position, we defocused the spot to keep it

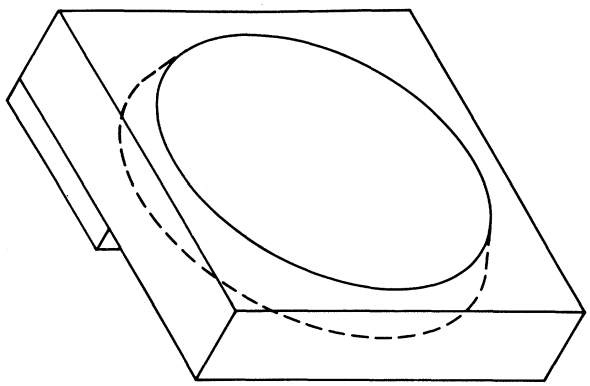

FIG. 1. Schematic of target used in measuring shock velocities. Energy from the laser pulse is deposited near the surface of the target (solid circle) and generates hot electrons, which redeposit the energy in the volume nearby (dashed region). The sudden heating of the target sets up a shock wave that traverses the foil and emerges frist from the substrate and later from the thin layer covering half of the back of the target. The thickness of the thin layer divided by the difference in emergence times is the average shock velocity.

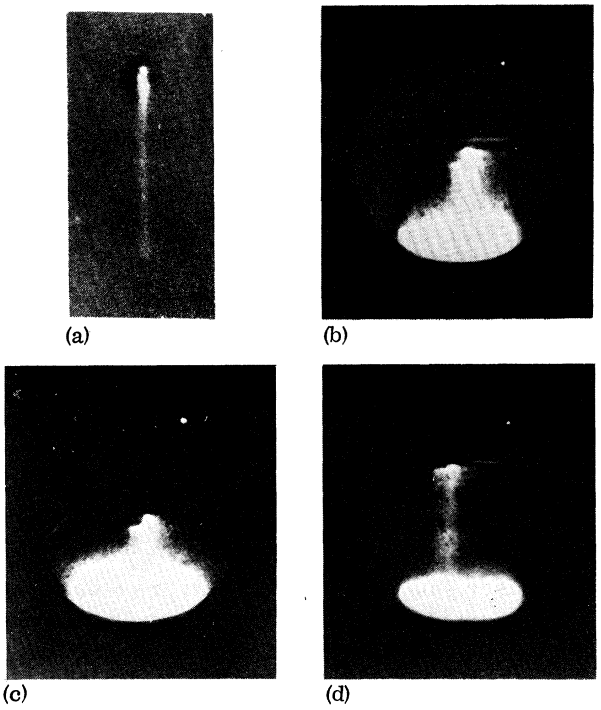

FIG. 2. Streak camera data for 13-μm-thick aluminum targets, each having an extra layer covering the left side of the spot struck by the laser. Time increases from top to bottom. The steps in the leading edges of the streaks indicate shock velcotieis of about 13 km/s and pressures of 200 GPa. Step thicknesses are (a) 3 μm, (b) and (c) 5 μm, and (d) 2 μm. The last three streaks, taken using the Pico V camera, show exposed areas at the bottoms because of a camera defect wherein the voltage on the streak plates returned to zero before the camera could be gated off.

larger than 100 μm to ensure planarity of the shock and uniformity of the spot illumination. (The hot electrons may also help uniformity by spreading the laser energy.) We used a system of lenses and mirrors to image the back of the target (viewed at 45°) onto the slit of a streak camera, and by triggering the camera at the appropriate time we could record the intensity of the light from the target as a streak on our film. When the target had a step, the leading edge of the streak also showed a step.

Figures 2(a)–2(d) show shock-velocity measurements for laser pulses of about 3×10^{14} W/cm^2 striking 13-μm-thick aluminum foils with steps. Time increases from top to bottom in the pictures. Figure 2(a) was taken using an Electrophotonics ICC-512 camera[6] to photograph a target with a 3-μm-thick step. The step in the leading edge of the streak appears as a notch in the upper left part of the streak and shows a time delay of 230 ps for the shock to traverse the 3-μm-thick layer, indicating a shock velocity of $U_s = 13$ km/s, which corresponds to a pressure[7] of about 200 GPa. (Billon *et al.*[3] report reaching a pressure of 170 GPa in polyethylene using a laser pulse of 3.5×10^{14} W/cm^2, and van Kessel[2] obtained pressures of 200 GPa in solid hydrogen and 400 GPa in Plexiglass with laser pulses of 2×10^{14} W/cm^2.) The other three pictures were taken using a Pico V camera.[8] Although it has more sensitivity and a larger dynamic range than the Electrophotonics, our version suffered two deficiencies: Its sweep speed was not as well characterized, giving a large (~30%) uncertainty in the velocity measurements; and the camera could not be pulsed off fast enough to prevent exposing a portion of the film when the voltage on the sweep plates returned to zero. Figures 2(b) and 2(c) show streaks from targets with 5-μm-thick steps, and Fig. 2(a) was for a 2-μm step. In each case the leading edge of the streak is at the top and the light from the thick part of the target is the left side of the streak. All three of the shock velocities and pressures appear to be similar to those of Fig. 2(a).

Streaks from 13-, 17-, 20-, and 25-μm foils become progressively dimmer as thickness increases, suggesting that we are observing a decaying shock wave. Similarly, the thinner side of a stepped foil appears brighter than the thicker side, although that is not apparent in Figs. 2(a) and 2(b) where the streaks are overexposed. These pictures are useful for shock-velocity measurement only. Figures 2(c) and 2(d) are overexposed for the thin side of the step, but well within the dynamic range of the Pico V for the thick side of the step. In Fig. 2(d) the difference in exposures is less because the step thickness is smaller.

Figure 3 shows a streak of light emerging from a 13-μm-thick planar foil struck by a 300-ps-long laser pulse of about 10^{15} W/cm^2 intensity. The streak, made with the Electrophotonics camera, shows an intense burst of light which lasts for about 1.2 ns and is followed by a dimmer tail lasting at least several nanoseconds longer. (Only the center of the tail is visible at this camera sensitivity.) Other streaks made using a variety of sensitivities and sweep speeds show that the transition from bright to dim is more gradual than Fig. 3 would indicate; the rather abrupt luminosity change appearing here is caused by the small dynamic range of the recording system.

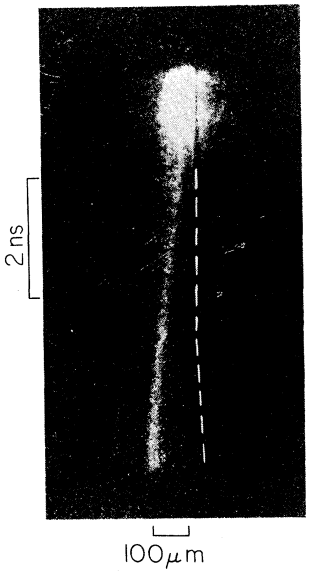

FIG. 3. Streak camera data for a 13-μm-thick aluminum target. The dotted line shows the center of the camera slit. Time increases from top to bottom. The movement of the streak away from the marker indicates that the radiating plasma is moving about 13 km/s in the laser-beam direction.

The dark line which runs through the streak (marked by a dashed line in the tail) was obtained by masking off a small region in the center of the slit. The deviation of the streak tail away from the dashed line corresponds to movement of the heated target in the same direction as the laser light was traveling before striking the target, and the magnitude of the deviation indicates a velocity of about 13 km/s for the light source. Of course, since we view the target at 45°, any change in size of the radiating plasma or in the depth from which the observed light originates will affect our measurement of its velocity relative to the center of the slit. Shock-velocity measurements for other foils of this thickness show that pulses of 10^{15} W/cm^2 produce shock velocities of about 14 km/s and particle velocities[7] of about 6.5 km/s; thus 13 km/s is a reasonable free-surface velocity. Remembering that measuring a free-surface velocity by this method is subject to interpretational difficulties, it is at least encouraging to find agreement between the shock velocity and what appears to be the velocity of the back of the foil. With adequate streak-camera dynamic range, we would expect to be able to measure this motion and the shock velocity simultaneously.

To study the rise and fall of the luminosity more carefully, we examined some the the Pico V streaks with a microdensitometer. Measurements of the intensities of steaks from planar foils show that the luminosity rises at least as fast as the resolution of the recording system (approximately 50 ps for these runs) and begins to decay almost immediately, dropping off more gradually in the tail than during the first nanosecond or so.

Luminosity risetimes of 50 ps or less for a shock velocity of 13 km/s imply that the thickness of the shock front, measured by its own luminosity, is less than 0.7 μm. Thus it is reasonable to observe the shock emerge separately from the two sides of a foil whose difference in thickness is as small as 2 μm [see Fig. 2(d)], although at the outset of this experiment we could not be sure that shock-velocity measurements would be possible. These observations are particularly encouraging because they suggest that it should be feasible to make EOS measurements for a variety of materials by means of impedance-match experiments in which the shock velocity is measured simultaneously in two materials, one whose EOS is known and one being studied, using a target made by evaporating a layer of each material onto opposite halves of the substrate. Newer versions of the Pico V camera, having subpicosecond time resolution, should enable us to measure shock velocities with uncertainties of about 1% if the luminosity risetimes prove fast enough.

In summary, we have seen that short laser pulses of intensities 3×10^{14} W/cm^2 and higher can be used to generate shocks in thin aluminum foils, that these shocks can be observed by their own luminosity, and that the shocks appear to dissipate somewhat as they transverse the foil. We have observed the motion of the shocked foil and hope to be able to deduce the free-surface velocity from similar observations. We have measured shock velocities of 13 km/s for laser pulses of 3×10^{14} W/cm^2 impinging on 13-μm-thick foils, and we have set upper limits of ≤ 50 ps on possible risetime and <0.7 μm on front thickness for a 200-GPa shock wave in aluminum.

We wish to thank the many people in the laser division of the Los Alamos Scientific Laboratory for their help in running the laser and fabricating the targets. Special thanks are due H. D. Sutphin, A. J. Lieber, A. J. Campillo, and S. L. Shapiro for lending us their streak cameras and helping us use them.

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[6]Hadland Photonics Limited, Newhouse Laboratories, Bovington, Herts HP3 OEL, United Kingdom.

[7]To find an approximate value for the pressure P we used the Hugoniot relationship $P=\rho_0 U_s U_p$ for an initially unshocked, cold material of density ρ_0, and we found the particle velocity from the expression $U_s=(5.238+1.338U_p)$ km/s given by R. G. McQueen, S. P. Marsh, J. W. Taylor, J. N. Fritz, and W. J. Carter, in *High-Velocity Impact Phenomena*, edited by Ray Kinslow (Academic, New York and London, 1970), p. 318.

[8]General Engineering and Applied Research Inc., 430 Sherman Ave., Palo Alto, Calif.

Fluctuations of the Ice-Water Interface during Solidification

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The dynamics of the freezing process is studied at the surface of a growing ice single crystal. Light ($\lambda = 488$ nm) is scattered by fluctuations of the nonequilibrium interface. The linewidth of the scattered light is proportional to the square of the scattering vector. For a scattering angle of 90° one measured about 2 krad/s. The intensity depends on the growth rate and shows a hysteresis in that dependence.

Light scattering from heterophase fluctuations at the interface between water and a growing single crystal has been observed. The dynamics of a nonequilibrium steady-state freezing process has been derived from the correlation function of the photon-count statistics. The ice-water system has been chosen for these investigations because the technique for growing large pure ice single crystals has been previously developed in our laboratory[1] and because the absorption of the 488-nm radiation of an argon-ion laser is weak.

Deionized and filtered water is purified by fifteen zone-refining passes. The resulting crystals have a dislocation density of about 1000 cm^{-2}.[1] The water in the molten zone is so pure that Rayleigh and Brillouin intensities together are as weak as the Raman intensity. A blue laser beam passing through the water appears to be reddish. In order to prevent contamination, the light scattering experiment is done *in situ* during a zone-refining cycle. The growth apparatus shown in Fig. 1 is placed in a cold room at −18°C. An acrylic glass tube (36 mm diam) is lowered through a heated zone into a cooled bath. The c axis of the crystal is oriented parallel to the

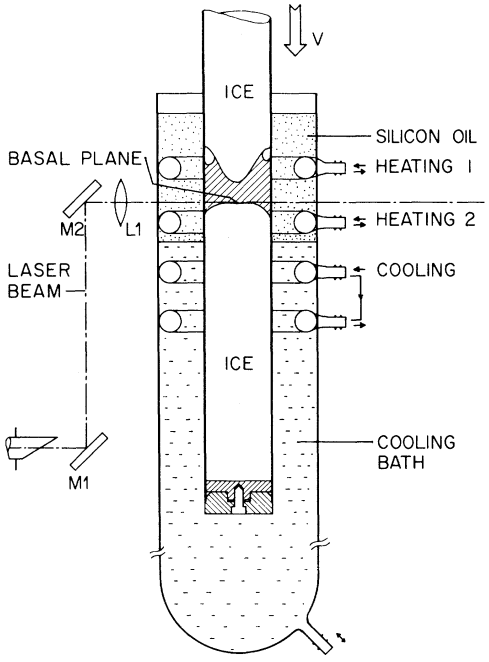
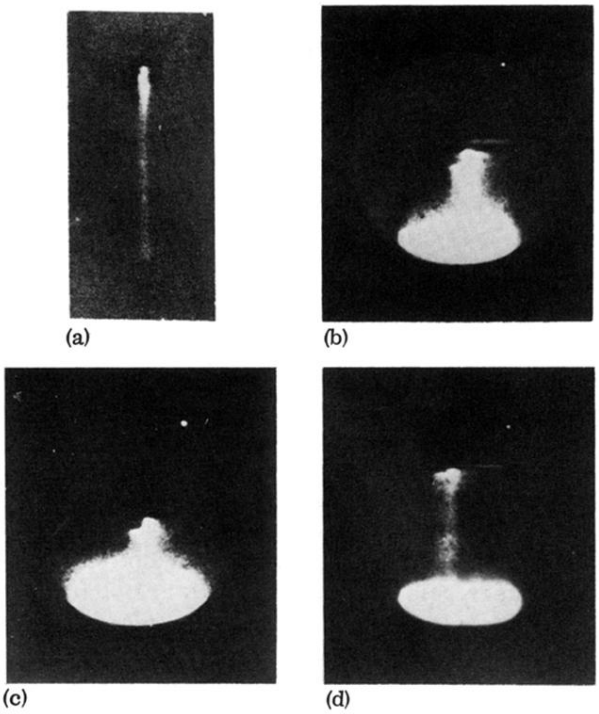


FIG. 1. Zone-refining apparatus in a cold room at −18°C.



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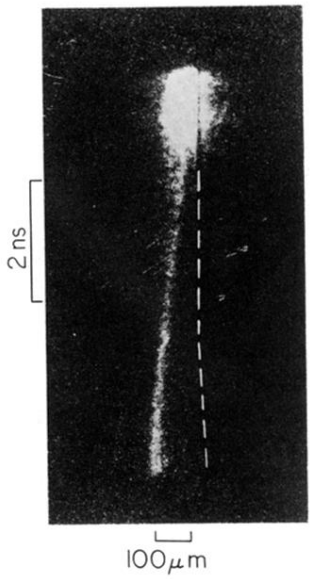

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