Impulsive Load Shock Wave in Condensed Matter with Realistic Equation of State

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Dedicated to Professor Dieter Pfirsch on his 60th Birthday

Laser-driven, impulsive load shock wave in plane, solid aluminum layers are investigated by hydrodynamic simulation, using a realistic equation of state. With a 10^{15} W/cm^2 laser pulse 30 ps long, a shock path $X_f = A \cdot t^\alpha$ is found with $\alpha = 0.73$, inconsistent with similarity solutions for this problem. It is shown that α depends most strongly on the cold pressure component; self-similar solutions, as discussed by Anisimov and Kravchenko, require that the thermal pressure becomes much larger than the cold one.

1. Introduction

High power lasers can generate strong shock waves in condensed matter [1]. In typical experiments, laser pulses less than 1 ns long are irradiated on a plane surface. The laser plasma ablating from a thin surface layer creates a short pressure pulse in the order of 10–100 Mbar. It drives a shock into the material with a typical velocity of about 10 km/s. Having an illuminated area of some 100 μm diameter, the shock front running into the layer stays approximately planar over a distance of a few 100 μm and over a time of about 10 to 50 ns. We investigate possibilities to extract equation of state information from measured shock trajectories.

The conditions described above are close to those of an impulsive load which is ideally defined as an infinitely short pressure pulse delivered to a free matter surface. If the pulse is applied to the plane surface of an ideal gas and if the pressure behind the shock front is much larger than the initial gas pressure (strong shock), the motion of the gas is described by a similarity solution and was discussed by Zeldovich and Raizer [2]. The shock front moves along a trajectory

$$X_f(t) = A \cdot t^\alpha, \tag{1}$$

where A and α are constants, and t is the time after the pulse.

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Typical profiles of density, pressure and velocity are illustrated in Figure 1. The shock weakens continuously by rarefaction to the vacuum on the left hand side, and the shock speed slows down. The similarity exponent α is therefore smaller than one; in general, conservation of energy and momentum constrain the exponent to values between $1/2 < \alpha < 2/3$, as derived in [2]. These results are valid for strong shocks; in the limit of weak pressure perturbations (sound waves), one has $\alpha = 1$.

In a recent paper, Anisimov and Kravchenko [3] showed that the similarity solution also exists for materials with a more complicated equation of state (EOS) of the type

$$p = \varrho\, e\, \Gamma(\varrho/\varrho_0), \tag{2}$$

where p is the pressure, ϱ the mass density, e the specific internal energy. The Grüneisen parameter Γ was chosen to depend on the compression ratio $G = \varrho/\varrho_0$ in the form

$$\Gamma(G) = 2/3 + (\Gamma_0 - 2/3) \cdot (G_m^2 + 1)/(G_m^2 + G^2) \cdot G, \tag{3}$$

which is an interpolation between the Grüneisen parameter Γ_0 at solid density ($G = 1$) and the ideal gas value $\Gamma = 2/3$ expected to hold at very high compression ($G \to \infty$). The parameter G_m determines the width of the transition region. Anisimov and Kravchenko proposed to determine G_m through laser experiments by measuring α for materials with known Γ_0. For this purpose, they calculated α for a few representative values of Γ_0 and G_m. It is important to note that, in the case of self-similar

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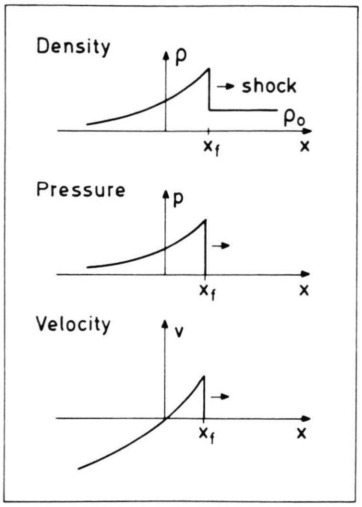

Fig. 1. Schematic drawing of density, pressure and velocity profiles corresponding to an impulsive load shock wave.

motion, the exponent α depends exclusively on the EOS properties of the material and not at all on initial conditions such as details of the pressure pulse applied; the strength of the pulse determines the amplitude A.

The Anisimov-Kravchenko proposal is of considerable practical interest, since it promises to provide EOS information by conceptually simple experiments in the pressure regime of 10 Mbar and above which is poorly investigated, so far. The goal of the present paper is to check this method in more detail. Since no experimental results are available at the moment, we decided to perform a "numerical experiment" by simulating laser driven shock waves in solid aluminum, using the SESAME EOS tables [4] as input. Although it may look irrational to extract EOS information from calculated shock trajectories based on EOS tables which are explicitly known, this procedure provides important new answers as to which extent self-similar trajectories of type (1) can be expected in real experiments and to what kind of information is actually contained in the exponent α.

2. The Numerical Experiment

In the numerical experiment, a 300 μm thick solid aluminum layer is illuminated with a 10^{15} W/cm^2 laser pulse of 30 ps duration, corresponding to 30 kJ/cm^2 absorbed energy. For a case in which a total energy of 100 J is absorbed, this corresponds to a laser spot of 600 μm diameter, and one can expect that the shock front running into the material is sufficiently planar over a distance of about 300 μm. These parameters are close to experimental parameters which can be achieved e.g. with the iodine laser ASTERIX at the Max-Planck Institute for Quantum Optics. Also, the iodine laser wavelength of 1.3 μm was chosen in the calculation, although one should use a shorter wavelength in real experiments to avoid problems with hot electrons.

The simulation was performed with the 1 D-Lagrangian hydrodynamic code LAPLAS. Typical calculations of this type are described in [5], including details about the laser-plasma coupling and the heat transport. In the context of the present paper, these details are of secondary importance, since the present focus is on the shock running into the depth of the Al layer, well separated from the laser-plasma region which serves simply as a means to generate the short pressure pulse.

For the shock propagation, the EOS input is essential. The SESAME EOS tables [4], used in the present calculation, were constructed from various physical models as well as empirical data and represent reasonably reaslistic EOS predictions which are now widely used in hot dense matter calculations. The SESAME pressure for Al is plotted versus density and temperature in Figure 2. In the low temperature region, one should notice the sharp pressure increase at densities just above the solid density of 2.7 g/cm^3. It is this region through which the principal Hugoniot runs and which is tested in the numerical experiment.

The calculated results are presented in Fig. 3 in the form of perspective plots which show the spatial and temporal evolution of density, temperature and pressure. The foil depth corrdinate represents the Lagrangian coordinate which marks each mass cell by its position at time $t = 0$ when the laser pulse sets in. The laser shines on the foil from the right, lower corner. On the time scale of 20 ns, the 30 ps pulse indeed creates impulsive load conditions. The pressure peak of more than 10 Mbar seen close to $t = 0$ decays by driving the shock wave into the foil and by material expansion, seen in the Lagrangian plot as decrease of density and pressure at the front surface. After 20 ns the shock has traveled about

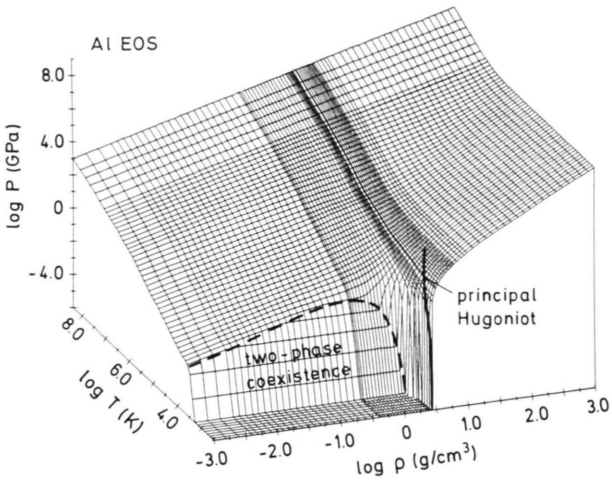

Fig. 2. Pressure versus density and temperature for Al from SESAME EOS tables [4].

260 μm into the foil. The shock position is plotted versus time in Fig. 4; it nicely follows the power law (1) with an exponent $\alpha = 0.73$. We have also run the same case with a 10^{14} W/cm^2, 300 ps pulse and obtained almost identical results.

3. Results and Discussion

The shock trajectory obtained in the numerical experiment based on the SESAME EOS is compared in Fig. 4 with other runs using simple model equations of state. The hydrodynamic simulation including the laser pulse is the same in all cases, except for changing the EOS input. In this way, we can check the consistency of the present calculation with the similarity solutions and can explore the sensitivity of the shock trajectory to various details of the equation of state.

The first remarkable result is that in all cases the shock paths follow the power law (1), almost within the accuracy of the drawing and allow to extract the exponent α rather uniquely. For an ideal gas EOS with adiabatic parameter $\gamma = 5/3$, we obtain $\alpha = 0.61$ in best agreement with the value $\alpha = 0.611$ resulting from the similarity analysis [2]. More important, we also reproduce the results of Anisimov and Kravchenko when using the EOS defined by (2), (3); with $\Gamma_0 = 2.19$ and $G_m = 0.65$ for Al, the result in Fig. 4 is $\alpha = 0.63$ as compared to $\alpha = 0.6312$ in [3]. For these tests, the internal energy was simply

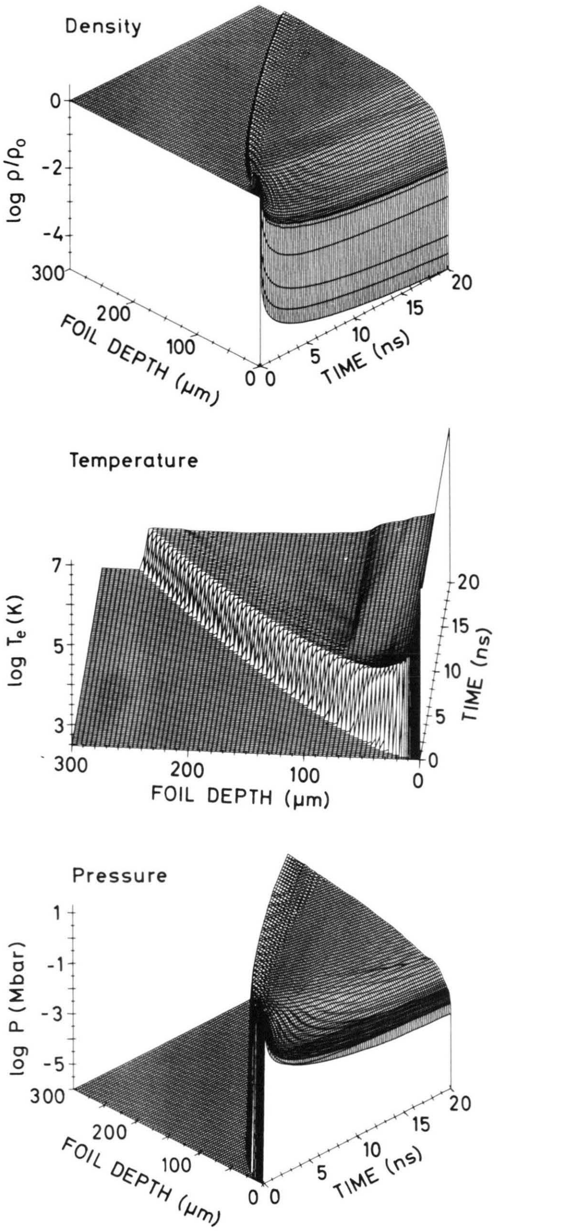

Fig. 3. Perspective plots of density, temperature and pressure versus foil depth and time obtained from the numerical experiment.

chosen as $e = 3k_B T/\mu$ where k_B is the Boltzmann constant and μ is the atomic mass.

The second important result is that the "realistic" value $\alpha = 0.73$ obtained with the SESAME EOS differs considerably from the values discussed by Anisimov and Kravchenko. This is particularly

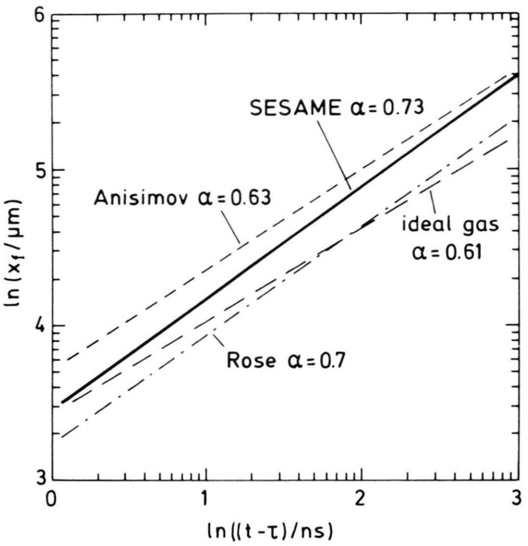

Fig. 4. Shock trajectories for different EOS. The parameter α gives the slope of the lines; the labels are explained in the text; $\tau = 15$ ps is the half-width of the laser pulse.

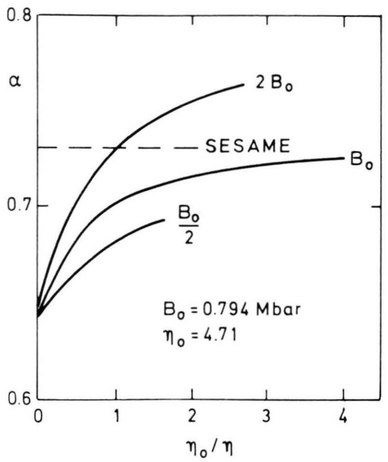

Fig. 5. Dependence of the shock parameter α on the bulk modulus B_0 and the anharmonicity parameter η_0/η occurring in the cold EOS parametrization of Rose et al. [6].

intriguing because $\alpha = 0.73$ lies outside the interval $1/2 < \alpha < 2/3$ to which self-similar solutions are restricted by the general requirements of energy and momentum conservation. We shall now discuss the reason for this discrepancy.

Apparently, the relations (2) and (3) only describe the thermal part of the equation of state and completely ignore the cold, elastic part which plays a dominant role for shock waves in condensed matter in the pressure regime considered here. The principal Hugoniot is seen in Fig. 2 to run through a steep pressure wall which is entirely due to the cold component. A reasonable model EOS should therefore add cold and thermal contributions

$$e(\varrho, T) = e_c(\varrho) + e_T(\varrho, T), \tag{4}$$

$$p(\varrho, T) = p_c(\varrho) + p_T(\varrho, T). \tag{5}$$

According to Rose et al. [6], the cold components can be parametrized in the form

$$e_c(\varrho) = e_c(\varrho_0) \cdot \exp(-a^*) \cdot (1 + a^* + 0.05 a^{*3}), \tag{6}$$

$$p_c(\varrho) = B_0 \cdot (3 r_{WSE}\, l / r_{WS}^2) \cdot \exp(-a^*) \cdot (-a^* + 0.15 a^{*2} - 0.05 a^{*3}), \tag{7}$$

where $r_{WS} = (3\mu/4\pi\varrho)^{1/3}$ with the atomic weight μ is the Wigner-Seitz radius and r_{WSE} the equilibrium value corresponding to ϱ_0, $a^* = (r_{WS} - r_{WSE})/l$ is the linear distortion scaled by the parameter l, and $B_0 = e_c(\varrho_0)/12\pi l^2 r_{WSE}$ is the bulk modulus at normal density. Relations (6) and (7) give a fairly accurate description of a large body of experimental and theoretical cold EOS data in terms of the zero pressured parameters, B_0 and $\eta_0 = r_{WSE}/l$.

In order to test the influence of the cold EOS on the shock parameter α, we added the cold components (6) and (7) to the corresponding thermal parts given by Anisimov and Kravchenko, taking $B_0 = 0.794$ Mbar and $\eta_0 = 4.71$ for Al as proposed by Rose et al. [6]. The resulting shock trajectory shown in Fig. 4 has $\alpha = 0.70$. Varying the cold EOS parameters B_0 and η leads to strong variations in α as shown in Figure 5. The SESAME result $\alpha = 0.73$ could be reproduced with a bulk modulus somewhat above 1 Mbar. It is concluded that the exponent α contains information on the cold EOS rather than on the thermal part.

4. Conclusions

Impulsive load shock waves in condensed matter, driven by short laser pulses with intensities in the range of 10^{15} W/cm^2, which are now achievable in high-power laser facilities, will not reach the self-similar regime described in the work of Anisimov and Kravchenko. The reason is that the expected shock pressures are still not high enough to satisfy "strong shock" conditions in the sense that the thermal pressure behind the front is much larger than the cold pressure. With peak pressures of 10−1000 Mbar during the laser pulse, one finds typical shock pressures of 1−10 Mbar during the coasting period which is available for measurements. In this region, Hugoniot pressures of materials like aluminum are still dominated by the cold, elastic EOS component.

Nevertheless, the shock trajectories obtained for typical laser conditions are well described by the power law $X_f(t) = A \cdot t^\alpha$ and allow to extract a well defined expoent α. This parameter contains valuable information on the high-pressure EOS, in particular on its cold part. We suggest systematic experiments to measure α.

Acknowledgements

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