THIN FOIL ACCELERATION METHOD FOR MEASURING THE UNLOADING ISENTROPES OF SHOCK-COMPRESSED MATTER

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Abstract. The thin foil acceleration method was tested in explosively-driven experiments with shock compressed PMMA and polyethylene at shock pressures up to 35 GPa. A transition was observed from the behavior expected for condensed matter to the gas-like response of the PMMA samples. Measurements of the PMMA unloading isentrope have been completed by modification of the equation of state in the vaporization region.

INTRODUCTION

This work has been performed as part of the search for possible ways to utilize the capabilities of laser and particle beams techniques in shock wave and equation of state physics. The peculiarity of these techniques is that we have to deal with micron-thick targets and not well reproducible incident shock wave parameters, so all measurements should be of a high resolution and be done in one shot.

Besides the Hugoniots, the experimental basis for creating the equations of state includes isentropes corresponding to unloading of shock-compressed matter. Experimental isentrope data are most important in the region of vaporization. With guns or explosive facilities, the unloading isentrope is recovered from a series of experiments where the shock wave parameters in plates of standard low-impedance materials placed behind the sample are measured [1,2]. The specific internal energy and specific volume are calculated from the measured $p(u)$ release curve which corresponds to the Riemann integral. This way is not quite suitable for experiments with beam techniques where the incident shock waves are not well reproducible.

The thick foil method [3] provides a few experimental points on the isentrope in one shot. When a higher shock impedance foil is placed on the surface of the material studied, the release phase occurs by steps, whose durations correspond to that for the shock wave to go back and forth in the foil. The velocity during the different steps, connected with the knowledge of the Hugoniot of the foil, allows us to determine a few points on the isentropic unloading curve. However, the method becomes insensitive when the low pressure range of vaporization is reached in the course of the unloading. The isentrope in this region can be measured by recording the smooth acceleration of a thin witness plate foil. With the mass of the foil known, measurements of the foil acceleration will give us the vapor pressure.

MEASURING THE UNLOADING ISENTROPE OF SHOCK-COMPRESSED PMMA

Earlier [4] evidence was found that vaporization of PMMA occurs at unloading after shock

DISCLAIMER

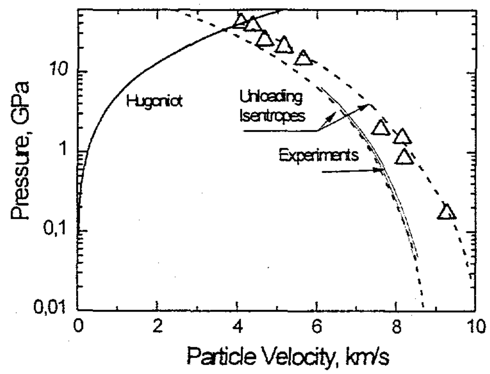

Figure 1. Unloading data for the shock-compressed PMMA.. Triangles present the data from ref. [4], the dashed lines were calculated using modified EOS, the thin lines at low pressures are the results of our experiments. Calculations have been done starting at a different initial shock pressures.

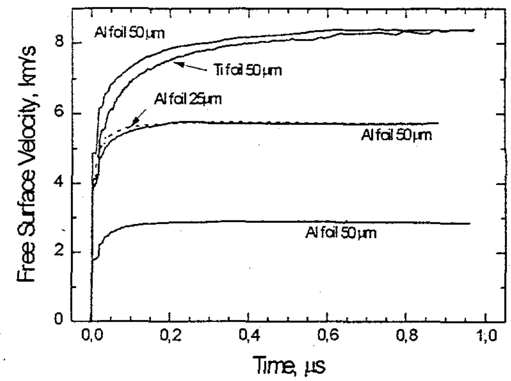

Figure 2. The velocity histories of the aluminum and titanium foils 25 or 50 μm thick covering PMMA sample plates. The peak shock pressures in the PMMA samples were 9 GPa, 23.8 GPa, and 34.5 GPa. .

compression to 40 GPa peak pressure. Fig. 1 presents the results of measurements of the unloading isentropes [4]. The data are presented in semi-logarithmic coordinates in order to demonstrate the behavior in low-pressure vaporization region. The measurements show the particle velocity increment in the unloading wave much exceeds that in the shock wave.

In explosively-driven experiments performed with the goal to test the possibility of studying unloading isentropes in the vaporization region, the shock waves with peak pressures in a range of up to 34.5 GPa were created in PMMA sample plates 1.7 to 1.8 mm thick using aluminum impactor plates 2 mm thick at an impact velocity of up to 5.3 km/s. The rear sample surfaces were covered by 25 μm to 50 μm thick aluminum or titanium foils. The velocity history of the foil surface was recorded with a VISAR velocimeter. The space behind the sample was evacuated.

Figure 2 shows the foil velocity histories measured in the experiments with PMMA at different peak pressures. According to computer simulations, a final constant velocity of the rear foil should be established after ~200 ns of the wave reverberation process. This behavior was observed in the experiments at lower shock pressures. However, the results of measurements at the highest peak pressures demonstrate a much longer time for the velocity increase and a somehwat higher final velocity. This finding is evidence of vaporization of the shock-heated PMMA at a 34.5 GPa peak pressure.

Fig. 3 illustrates the interpretation of the measured velocity histories. The upper parts of the velocity profiles have been approximated by a smooth function $u_f(t)$ with monotonically decreasing first and second derivatives. Knowing the foil mass, the vapor pressure was evaluated using Newton's law as $p(t)=\rho\cdot\delta\cdot du_f(t)/dt$, where ρ and δ are the foil density and thickness. The values of the pressure, p, and the particle velocity, $u=u_f$, taken at the same time moment t correspond to a point on the unloading isentrope of the shock-compressed PMMA.

The results of this treatment are shown in Fig. 1 by thin lines in the low pressure part of the *p-u* diagram. It is seen that the experiments with aluminum and titanium witness foils of different mass are in a good agreement. Our data show the same trend as the data of ref. [4] and in this sense may be considered as quite reasonable. Next we explore the modification of an EOS model and the adjustment of the model parameters by means of computer simulations.

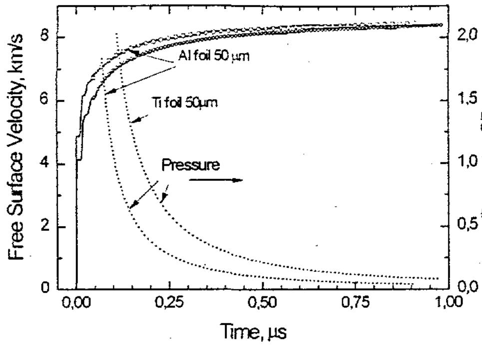

Figure 3. Interpretation of the measured velocity history. The points are the approximation; the dashed lines show the pressure histories calculated from the foil acceleration.

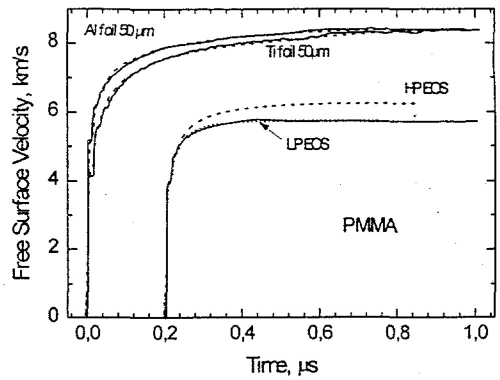

Figure 4. Comparison of measured (solid lines) and simulated (dashed and dot-dashed lines) velocity histories of aluminum and titanium witness foils at 34.5 GPa (top curves) and 23.8 GPa (lower curves) of the incident shock pressures. The high-pressure (HP EOS) and low-pressure (LP EOS) versions of the equation of state were used in simulations of the 23.8 GPa shot.

PMMA EQUATION OF STATE IN THE VAPORIZATION REGION.

Caloric Mie-Gruneisen's equation of state (EOS) generalized to account for gas phase states [4] was used to describe the experimental data on thin foil acceleration by shock-compressed PMMA. The generalized Mie-Gruneisen EOS was used with the elastic energy expressed as follows

$$E_c(V) = \frac{B_{0c}V_{0c}}{m-n}\left(\frac{\sigma_c^m}{m} - \frac{\sigma_c^n}{n}\right) + E_d,$$

where $\sigma_c = V_{0c}/V$, V_{0c}, and B_{0c} are the specific volume and the bulk modulus at p=0, T=0 K, $E_d = B_{0c}V_{0c}/mn$. The Gruneisen parameter $\Gamma(V,E)$ was defined as

$$\Gamma(V,E) = \gamma_i + \frac{\gamma_c(V) - \gamma_i}{1 + \sigma_c^{-2/3}[E - E_c(V)]/E_a},$$

where the expression for $\gamma_c(V)$ refers to low thermal energies, and γ_i characterizes the region of strongly heated condensed matter. The volume dependence of coefficient γ_c is

$$\gamma_c(V) = \frac{2}{3} + \left(\gamma_{0c} - \frac{2}{3}\right)\frac{\sigma_n^2 + \ln^2\sigma_m}{\sigma_n^2 + \ln^2(\sigma/\sigma_m)},$$

where $\sigma = V_0/V$.

Figure 1 shows unloading isentropes calculated with the EOS parameters V_{0c}=8.212·10^{-4} m^3/kg, B_{0c}=7.786 GPa, m=1.33, n=2.67, σ_m=0.3, σ_n =1.0, γ_{0c}= 0.9, γ_i=0.5, and E_a=4·10^7 J/kg. Results of 1-D computer simulations of the shock-wave experiments with these EOS parameters are shown in Fig. 4. The simulations reproduce well the experimental data at high pressure but don't agree with the experimental data at lower shock intensities. The good agreement of the simulated and measured foil velocity histories at 34.5 GPa incident shock pressure may be considered as an evidence of reliability of the thin foil acceleration method for investigation of EOS properties in the vaporization region. There is probably more than just vaporization occuring in PMMA after shock compression up to high pressures. E. Hauver [5] observed a rapid increase in the shock polarization and dielectric constant at shock pressures of 26.7 GPa and higher while the relaxation time of polarization suddenly decreased. These results may be considered as evidence of some physical or chemical transformation in the shock-compressed PMMA. In this case we should use a different EOS for the incident and transformed matter. Figure 4 shows also the results of simulations at 23.8 GPa peak pressure using the same EOS with the parameters V_{0c}=8.415·10^{-4} m^3/kg, B_{0c}=7.599 GPa, m=1.0, n=3.0, σ_m=0.5, σ_n =1.0, γ_{0c}= 0.2, γ_i=0.2, and E_a=1.0·10^7 J/kg.

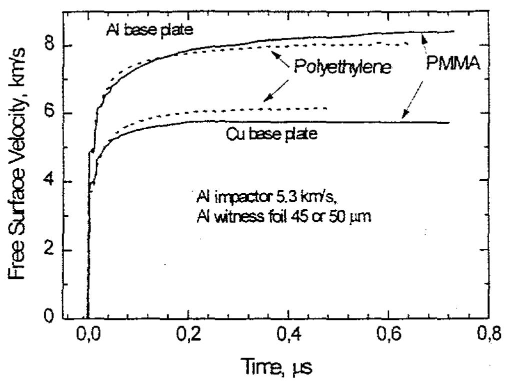

Figure 5. The acceleration histories of aluminum witness foils accelerated by shock-compressed polyethylene and PMMA. The foil thickness was 50 µm in shots with PMMA samples and 45 µm in the case of polyethylene. The peak shock pressure was varied using the base plates of different dynamic impedances at the same impact velocity of 5.3 km/s.

BEHAVIOR OF POLYETHYLENE AT UNLOADING

Figure 5 presents results of measurements of acceleration of aluminum witness foils by shock-compressed polyethylene in comparison with the similar data for PMMA. While the foil acceleration was recorded for the high-pressure shot with polyethylene for at least 0.6 µs, the magnitude of the acceleration was much less than in the case of PMMA at the same impact conditions.

Figure 6 presents results of a simulation of the witness foil acceleration with the EOS parameters V_{0c}= $1.008\cdot10^{-3}$ m^3/kg, B_{0c}=9.911 GPa, m=3.3, n=0.7, σ_m=0.8, σ_n =1.0, γ_{0c}= 0.7, γ_i=0.35, and $E_a=1.0\cdot10^8$ J/kg. The measured velocity profile deviates from the calculated one when the velocity 7800 m/s is passed. The maximum recorded velocity is 8050 m/s; the foil acceleration in this range corresponds to the vapor pressure decrease from 170 MPa down to nearly zero.

CONCLUSION

The thin foil acceleration technique for measuring the unloading isentrope of shock-compressed materials in a vaporization region has been suggested and tested in explosively-driven experiments with PMMA and polyethylene samples using aluminum and titanium foils of different mass. Measurements of the PMMA unloading isentrope have been completed by correction of the PMMA equation of state in the vaporization region. A computer simulation of shock-wave experiments confirms the validity of the method. The technique should be effective when it is used with particle beams as the shock wave generators [6].

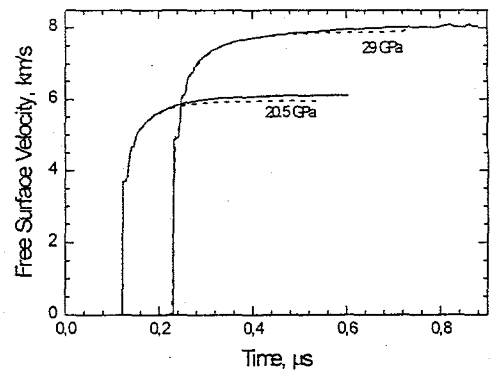

Figure 6. Comparison of measured (solid lines) and simulated (dashed lines) velocity histories of aluminum witness foils accelerated by shock compressed polyethylene.

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