DETERMINATION OF SHOCK ADIABATS OF LOW-DENSITY MATERIALS

L. V. Al'tshuler, G. S. Doronin, and S. V. Klochkov

UDC 620.178.73

The study of the behavior of shock adiabats of materials with a reduced initial density make it possible to judge the state of the material at high pressures and temperatures. Shock adiabats are usually determined at high pressures and temperatures. Shock adiabats are usually determined by the reflection method [1]. A shock wave is introduced into the sample from a barrier with a known shock adiabat. The velocity of the shock wave in the barrier and in the sample under study is recorded. The mass velocity in the material under study is determined from the measured values of the velocity of the shock wave and the shock adiabat of the barrier material. The pressure p and the relative compression σ of the material on the shock adiabat are determined from the conservation laws:

$$p = \rho_0 Du,\ \sigma = \rho/\rho_0 = D/(D-u),$$

where ρ_0 is the initial density of the material under study; ρ, density of the material behind the shock front; D, velocity of the shock wave; and u, mass velocity.

Other methods used [2, 3] employ several electromagnetic transducers to determine the velocity of the shock wave and the mass velocity in the material under study.

All these methods of determining shock adiabats give good results for weakly compressible materials. Methods [1-3] do not accurately determine the relative compression of low-density highly compressible materials on a shock adiabat. In low-density materials the velocity D of the shock wave and the mass velocity u are nearly the same, and therefore there is a large error in the determination of their difference when these quantities are measured independently. This in turn leads to appreciable errors in the determination of the relative compression of the material behind the shock front.

To increase the accuracy of the determination of the relative compression of the material behind the shock front we propose a method which permits a direct measurement of the time interval proportional to D—u. To do this a shock wave with constant parameters behind the front is introduced into the same under study from the barrier, and an electrically conducting needle with a dynamic rigidity appreciably greater than that of the sample material is placed at a distance h_0 from the barrier. The shock-compressed material behind the shock front flows around such a needle, leaving it practically stationary. The time t_1 for the shock wave to pass from the barrier to the needle point, and the time Δt from the instant the shock front approaches the point to the contact of the needle with the barrier-sample interface are measured. Figure 1a shows the x—t diagram of the propagation of a shock wave through the sample under study (OA is the trajectory of the shock front and OB is the path of the barrier—sample interface).

The velocity of the shock wave and the mass velocity in the sample are determined by the equations

$$D = h_0/t_1,\quad u = h_0/(t_1 + \Delta t).$$

It follows from the x—t diagram that $\Delta t = h_0/u - h_0/D$, so $D - u = \Delta t\, Du/h_0 = h_0\, \Delta t/[t_1(t_1 + \Delta t)]$, and the relative compression of the material behind the shock front is

$$\sigma = \rho/\rho_0 = D/(D-u) = (t_1 + \Delta t)/\Delta t = t_1/\Delta t + 1; \tag{1}$$

and the pressure behind the shock front is

$$p = \rho_0 Du = \rho_0 h_0^2/[t_1(t_1 + \Delta t)]. \tag{2}$$

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 138-141, November-December, 1985. Original article submitted July 31, 1984.

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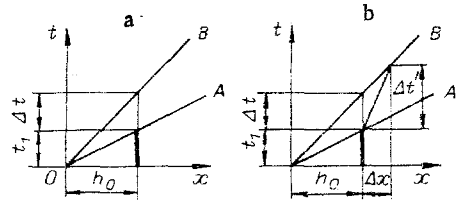

Fig. 1

It is easy to show [4] that in findng a shock adiabat by the methods in [1-3] the relative error $\varepsilon(\sigma)$ in the determination of the relative compression of the material is given by the formula

$$\varepsilon(\sigma) = (\sigma - 1)\sqrt{\varepsilon^2(D) + \varepsilon^2(u)}, \tag{3}$$

where $\varepsilon(D)$ and $\varepsilon(u)$ are the relative errors of the measurement of the velocity of the shock wave and the mass velocity in the material under study. In using the proposed method the error $\varepsilon(\sigma)$ is determined by the relation

$$\varepsilon(\sigma) = \sqrt{\varepsilon^2(t_1) + \varepsilon^2(\Delta t)}, \tag{4}$$

where $\varepsilon(t_1)$ and $\varepsilon(\Delta t)$ are the relative errors in the determination of the time intervals t_1 and Δt. The values of t_1, Δt, D and u are about equally accurate, i.e., the radicands in Eqs. (3) and (4) are equal to one another. The relative error of the relative compression in the method proposed does not depend on the relative compression of the material, while in methods [1-3] it is proportional to $(\sigma - 1)$. Therefore, for a relative compression $\sigma > 2$, i.e., for the compression of low-density materials, the accuracy of the determination of a shock adiabat by the proposed method will be higher than with the methods in [1-3].

In deriving Eqs. (1) and (2) it was assumed that the needle behind the shock front remains stationary. The displacement of the needle in the shock-compressed material introduces a systematic error into the results of the measurements. We estimate the magnitude of the error introduced into the determination of the relative compression by the displacement of the needle.

We assume that the average rate of displacement of the needle is constant and equal to αu, where α is a constant $(0 < \alpha < 1)$. Then the displacement of the needle in the time $\Delta t'$ is $\Delta x = \alpha u \Delta t$. The x–t diagram in Fig. 1b shows the shock wave process in the sample, allowing for the displacement of the needle. The notation is the same as in Fig. 1a. It follows from the x–t diagram that

$$\alpha u \Delta t' + h_0 = u(t_1 + \Delta t'),$$

from which

$$\Delta t' = (h_0/u - t_1)/(1 - \alpha),$$

but $h_0/u = t_1 + \Delta t$, and $\Delta t' = \Delta t/(1 - \alpha)$. The true σ and the apparent σ values of the relative compression of the material in the shock wave have the form

$$\sigma = t_1/[\Delta t'(1 - \alpha)] + 1, \quad \sigma' = t_1/\Delta t' + 1.$$

The systematic error introduced into the determination of the relative compression by the displacement of the needle is

$$\varepsilon(\alpha) = \frac{\sigma - \sigma'}{\sigma} = \frac{\alpha}{1 + \frac{\Delta t'}{t_1}(1 - \alpha)} = \frac{\sigma - 1}{\sigma}\alpha. \tag{5}$$

It follows from (5) that $\alpha/2 < \varepsilon(\alpha) < \alpha$ for $\sigma > 2$.

To estimate the effect of the displacement of the needle on the accuracy of the determination of the shock adiabat parameters we measured the average rate of displacement of steel and tungsten needles behind a shock front in water. From the average rate of displacement we calculated the systematic error introduced into the determination of the relative compression of the material behind the shock front.

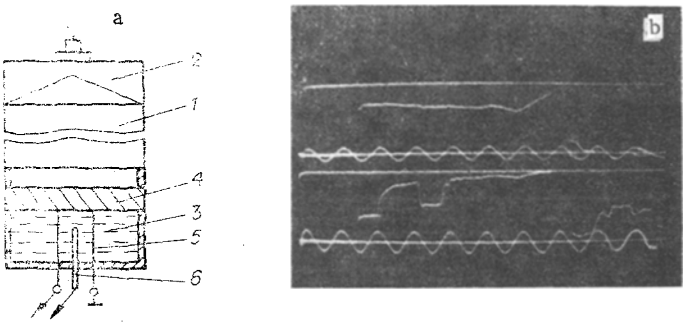

Fig. 2

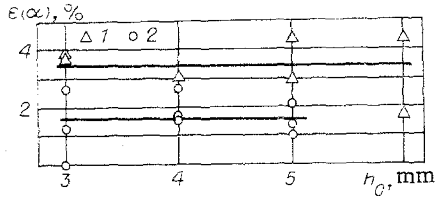

Fig. 3

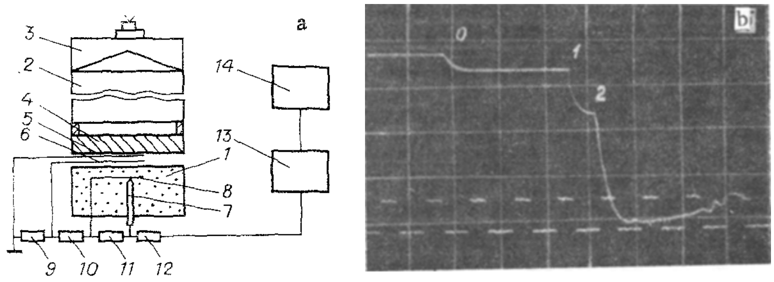

Fig. 4

A schematic diagram of the experimental arrangement is shown in Fig. 2a. The charge 1 is 84 mm in diameter and 100 mm high, and when it is detonated by the plane wave generator 2 a shock wave of amplitude 9.19 GPa with constant parameters behind the front is excited in a layer of water 3 separated from the charge by an air gap and a barrier 4. A Π-shaped electromagnetic transducer 5 of 0.07-mm-thick aluminum foil was placed on the barrier–water interface. A 1-mm-diameter steel or tungsten needle 6 was placed between the transducer foils at a distance h_0 from the barrier. The whole arrangement was placed in a uniform magnetic field of 450 e.

It was shown in [5] that water in a shock wave with an amplitude of ∿9 GPa partially dissociates into ions. As the shock front approaches the needle point a potential difference develops between the needle and the aluminum transducer as between metal electrodes with different electrochemical properties. This potential difference disappears with the content of the transducer on the needle.

The profile of the mass velocity at the water–barrier interface recorded by the electromagnetic transducer is fed into the first channel of an OK-33 oscillograph, and the sum of the signals from the electromagnetic transducer and the needle are fed into the second channel. An oscillogram is shown in Fig. 2b. The frequency of the time markings is 1 MHz. The first jump of the signal in the second channel corresponds to the instant the shock wave enters the sample, the second to the approach of the shock wave to the needle point, and the third to the contact of the transducer with the needle. The time intervals t_1 and $\Delta t'$ were found from these.

The average relative rate of displacement of the needle is determined from the expression

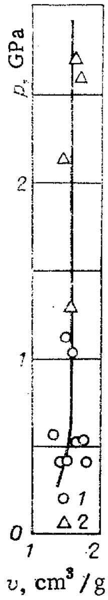

Fig. 5

$$\alpha = \frac{\Delta x}{\Delta t' u} = \frac{\int_0^{t_1+\Delta t'} u(t)\,dt - h_0}{\Delta t' u},$$

where u is the mass velocity of the water behind the shock front recorded by the electromagnetic transducer. The integration is performed numerically over the experimental mass velocity profile. It was determined that in water moving behind the shock front with a mass velocity of 1.86 km/sec the average rate of displacement of the steel needle is 0.174 km/sec, and that of the tungsten needle 0.080 km/sec. Accordingly, the values of the average relative rate of displacement α of a needle were 0.096 and 0.044.

Using the values of α from Eq. (5), we calculated the systematic error in the determination of σ introduced by the displacement of the needle when it was located at various initial distances from the barrier. The results obtained for the steel (points 1) and tungsten (points 2) needles are shown in Fig. 3, from which it follows that the average error ε(α) introduced by the displacement of the tungsten needle in water was 1.6%. In using a tungsten needle to determine shock adiabats of materials substantially less dense than water, this error can generally be neglected. By using the method described we determined the shock adiabat of porous polystyrene with an initial density $\rho_0 = 0.1$ g/cm³.

A schematic diagram of the experimental arrangement is shown in Fig. 4a. A plane shock wave with constant parameters behind the front was introduced into sample 1 under study by using an explosive device. The arrangement contains an explosive charge 84 mm in diameter and 100 mm high with a plane wave generator 3 and a barrier 4 separated from the charge by an air gap. A contact transducer consisting of two copper foils 5 and 6 each 0.02 mm thick separated by lacquer insulation was located on the barrier—sample interface. If the material being studied behind the shock front has an appreciable conductivity, the foils must be insulated from the sample in order to eliminate their premature short circuiting with the contacts of the second transducer. The thickness and material of the insulation are chosen from the specific conditions of the experiment. A second contact transducer was placed in the sample under study at a distance h_0 from the boundary with the barrier. One electrode of the transducer was the 1-mm-diameter tungsten needle 7 mounted perpendicularly to the barrier, and the second was a 0.02-mm-thick copper foil 8 insulated from the needle point by a layer of lacquer insulation. Foils 5 and 6 of the first transducer, needle 7, and foil 8 of the second transducer are connected by resistors 9-12 with a bridge circuit and a pulsed current source 13. The potential difference from the diagonal of the bridge circuit is fed into oscillograph 14. Power to resistors 9-12 is supplied by a sync circuit (not shown in Fig. 4) before the shock wave reaches the same under study.

As the shock wave passes through the sample there is a successive closing of contacts 5 and 6 of the first transducer, the needle and contact 8 of the second transducer, and the needle with contact 6 moving together with the barrier—sample boundary. During this, resistors 9-11 are short-circuited. At the instant of closing of the transducers there is a change of the potential difference in the diagonal of the bridge circuit. This leads to a deflection of the beam on the oscillograph screen. An oscillogram is shown in Fig. 4b. The time markings are 1 MHz. Point 0 corresponds to the instant the shock wave enters the sample, point 1 to the instant the wave front approaches the needle point, and point 2 to the contact of the needle with the barrier—sample interface. The time intervals t_1 and Δt were determined from the times of deflection of the beam. The parameters on the shock adiabat were calculated with Eqs. (1) and (2). During the determination of the shock adiabat the state behind the shock front in polystyrene was assumed steady. Nonequilibrium processes such as dissociation and evaporation, which are possible in a shock-compressed porous material were not considered.

Figure 5 shows a shock adiabat of porous polystyrene with an initial density of 0.1 g/cm^3 in p—v coordinates (specific volume). Points 1 were obtained by the method described in the present article, and points 2 were taken from [6] where they were determined by the "reflection method" on laboratory explosive stands. The good agreement of our results and the data of [6] confirms the effectiveness of the method described.

The recording circuit presented here with an external pulsed current source is not the only one possible. The instant the shock wave enters the sample, the arrival of the shock wave at the needle, and the contact of the needle and the barrier—sample interface can be fixed by various electrical effects arising in the shock-compressed material under study, as was done, for example, in determining the displacement of the needle behind the shock front in water.

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