SHOCK COMPRESSIBILITY OF POLYSTYRENE OF VARIABLE INITIAL DENSITY

I. P. Dudoladov, V. I. Rakitin, Yu. N. Sutulov, and G. S. Telegin

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The dynamic compressibility of polystyrene $[C_6H_5 - CH - CH_2]_n$ with initial densities of 1.0, 0.7, 0.5, and 0.3 g/cm^3 has been investigated at pressures of 200–400 kbars. The D–ρ_0 (wave velocity-initial density) relations are presented for specimens of normal and reduced density tested under identical conditions. Wave velocity-particle velocity relations are given for polystyrene of normal and reduced density together with the shock Hugoniots. The simplest equation of state satisfactorily describing the entire set of experimental data is selected.

The shock compressibility of polystyrene of variable initial density was studied by the "reflection method" described in detail in [1–3]. The pressures realized in the test specimens were obtained by means of the measuring devices described in [4, 5]. The propagation velocity of the shock waves in the specimens was registered by the electrical contact method. Copper and aluminum disks were used to screen the specimens. The shock Hugoniots of the screens were taken from [5] in the form

$$\begin{aligned} D &= 5.25 + 1.39u \quad (0 < u < 5) \text{ aluminum} \\ D &= 3.95 + 1.50u \quad (0 < u < 4) \text{ copper} \end{aligned} \tag{1}$$

where D is the shock wave velocity [km/sec] and u is the particle velocity [km/sec].

The material of the screens and the corresponding particle velocities for the measuring devices employed are presented in the left-hand columns of Table 1.

Table 1

No. of measuring device	Screen material	u [km/sec]	A	B
1	Al	0.69	1.276	2.123
2	Al	1.51	2.998	2.54
3	Cu	1.76	3.70	2.669
4	Al	2.76	6.05	1.22
5	Al	2.82	6.63	0.776
6	Al	3.70	8.23	1.181

The experiments were organized in two variants. In one series of experiments the test specimens were prepared in the form of disks 40 mm in diameter and 4 mm thick. In another series the specimens took the form of tablets 12 mm in diameter and 4 mm thick. In the first case all the contacts were located in a single specimen, and in the second case three tablets were measured at the same time.

Both series of experiments are illustrated in Fig. 1, where S denotes the shock wave, 1 the specimen, 2 the screen, and 3 the electrical contacts.

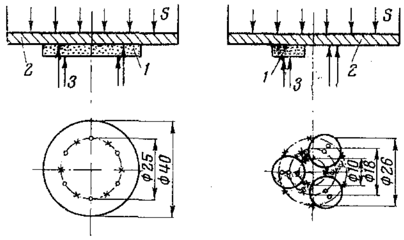

Fig. 1

As a direct result of the experiments we obtained the recorded wave velocities in the test specimens.

The experimental data on the dynamic compressibility of polystyrene of variable density are presented in Fig. 2. Along the ordinate axis we have plotted the wave velocities D, and along the axis of abscissas the starting densities of the specimens ρ_0; points 1 relate to the first series of experiments, points 2 to the second series. The bars indicate the maximum spread of the wave velocities obtained for specimens tested in the second series.

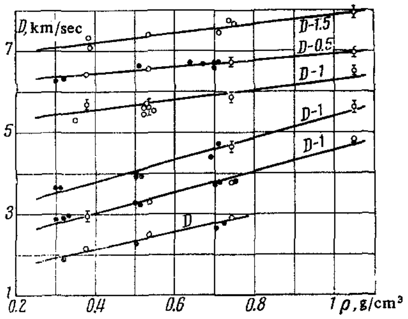

Fig. 2

As the figure shows, in all cases as the density of the specimens increases, so do the wave velocities. This tendency is strongly expressed for "weak" systems and less noticeable for explosive devices creating strong shocks. In general, the experimental results for the individual charges lie close to straight lines. Analytically, the D–ρ_0 relations were approximated by linear equations of the type $D = A + B\rho_0$, whose coefficients were found by the method of least squares. Numerical values of the coefficients are presented in the right-hand side of Table 1.

The data presented in the D-ρ_0 diagram and in Table 1 determine the values of the wave velocities for a broad range of pressures and initial densities. The authors selected four density values for further analysis: 0.3, 0.5, 0.7, and 1.05 g/cm³. The values of the particle velocities were found by a graphic construction from the pressure-velocity diagrams, while the pressures and densities were obtained from the conservation laws

$$P = \rho_0 D u \tag{2}$$

$$\rho = \rho_0 D/D-u \tag{3}$$

In Fig. 3 the shock Hugoniots of polystyrene with densities 0.3, 0.5, 0.7 and 1.05 g/cm³ are presented in D–u coordinates.

The same figure includes the results of American investigators for polystyrene with ρ_0 = 1.05 g/cm³ (points 1 from [6], points 2 from [7], and points 3 from [8]).

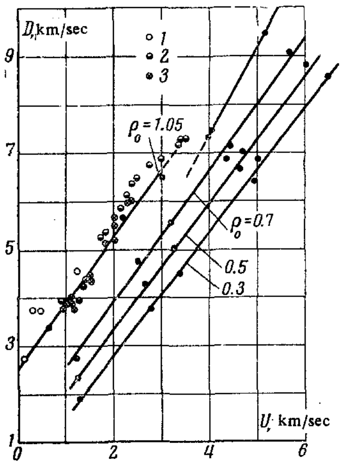

Fig. 3

Clearly, the data of [6,7] lie above the straight line obtained by the authors. The phase transformation reported by Hauver [7] in polystyrene is confirmed by our experiments. The D–u relations in Fig. 3 are described by equations of the type

$$D = c_0 + \lambda u \tag{4}$$

with coefficients c_0 and λ found by the method of least squares with allowance for the statistical weights. The latter were assumed proportional to the number of measurements made on specimens of a given type. Values of the coefficients c_0 and λ are presented in Table 2.

Table 2

Density [g/cm³]	c_0 [km/sec]	λ	Interval with respect to u
0.3	0.15	1.29	$1.2 < u < 6.5$
0.5	0.70	1.31	$1.2 < u < 6.2$
0.7	1.19	1.35	$1.2 < u < 5.7$
1.05	2.51	1.36	$0 < u < 3$

The shock Hugoniots characterizing the compressibility of foam polystyrene of variable density have been plotted in P–σ ($\sigma = \rho/1.05$) coordinates in Fig. 4 using Eqs. (2)–(4). The curves corresponding to the highly porous specimens, which accumulate large amounts of thermal energy during shock compression, are the steepest.

For these specimens the resistance to shock compressions at high pressures is determined almost entirely by the thermal pressure of the partially dissociating molecules of foam polystyrene.

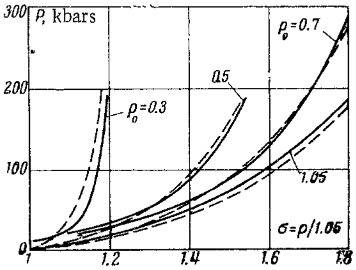

Fig. 4

For the upper points on the left-hand curve $\rho_0 = 0.3\,\mathrm{g/cm^3}$, the ratio of the thermal pressure to the thermal energy density

$$\gamma = \frac{P_T}{\rho E_T} \approx \frac{2}{\rho_r(1/\rho_0 - 1/\rho_r)} = 0.58$$

The value $\gamma = 0.6$ gives the best description of the experimental data.

This important thermodynamic parameter was used in selecting the simplest equation of state relating the pressure P and the internal energy E:

$$P - P_x = (E - E_x)\gamma\rho, \quad P_x = -\frac{dE}{dv} = \frac{\rho_0 c_0^2}{n}(\sigma^n - 1) \tag{5}$$

In this equation P_x gives the resistance to compression at absolute zero ($\rho_0 = 1.05\,\mathrm{g/cm^3}$, $n = 4.4$, $c_0 = 2.3\,\mathrm{km/sec}$).

The selected form of the equation of state leads to the following equations for the dynamic adiabat:

$$P_g = \frac{\rho_0 c_0^2}{n(h - k\sigma)}\left[\left(h - \frac{n+1}{n-1}\right)\sigma^n + \frac{2n}{n-1}\sigma - (h+1)\right] \tag{6}$$

and the isentropes

$$P_s = P_x + \left(\frac{\sigma}{\sigma_g}\right)^{(h+1)/(h-1)}[P_g(\sigma_g) - P_x] \tag{7}$$

In Eqs. (6) and (7) $h = 1 + 2/\gamma = 4.35$, and $k = 1.05/\rho_0$ is the "porosity" coefficient.

The curves calculated from Eq. (6) are indicated by dashed lines in Fig. 4. They satisfactorily describe the behavior of porous and solid polystyrene up to the region of phase transformation. The isentropes can be found via Eq. (7). As for the isotherms, their position cannot be established at all accurately, since the specific heat of foam polystyrene and the dissociation energy of its molecules are known with a low degree of accuracy.

REFERENCES

1. L. V. Al'tshuler, K. K. Krupnikov, B. N. Ledenev, V. N. Zhuchikhin, and M. I. Brazhnik, "Dynamic compressibility and equation of state of iron at high pressures," ZhETF, vol. 34, no. 4, 1958.
2. Solid State Physics, vol. 6, Acad. Publ., New York, 1958.
3. L. V. Al'tshuler, "Applications of shock waves in high-pressure physics," Usp. fiz. nauk, vol. 85, no. 2, 1965.
4. L. V. Al'tshuler, M. N. Pavlovskii, L. V. Kuleshova, and G. V. Simakov, "Investigation of alkali metal halides at high shock-compression pressures and temperatures," Fizika tverdogo tela, vol. 5, no. 1, 1963.
5. L. V. Al'tshuler, S. B. Kormer, A. A. Bakanova, and R. F. Trunin, "Equation of state of aluminum, copper, and lead for the high-pressure region," ZhÉTF, vol. 38, no. 3, 1960.
6. M. H. Wagner and W. F. Waldorf, Compendium of Shock Wave Data, Vol. 2, Univ. California, 1966.
7. G. E. Hauver, "Shock-induced polarization in plastic, II: Experimental study of plexiglas and polystyrene," J. Appl. Phys., vol. 36, no. 7, 1965.
8. J. Berger, Compendium of Shock Wave Data, Vol. 2, Univ. California, 1966.

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