Experimental confirmation of shell effects on the shock adiabats of aluminum and lead

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Data have been obtained on the shock compressibility of aluminum and lead with respect to iron at pressures in the ranges 35–240 and 80–550 Mbar, respectively. These results provide the first reliable confirmation of a manifestation of shell effects on the shock adiabats of dense materials.

Several theoretical studies (e.g., Refs. 1 and 2) have established that the shell structure of an atom affects the thermodynamic properties of dense materials. In particular, it leads to an oscillation in the shock adiabats with respect to the smooth interpolation curves constructed from experimental data at low pressures and results found from a modification of the statistical Thomas-Fermi model to reflect the regular quantum corrections[3] and the nonideal properties of the ion cores.[4]

If we wish to take shell effects into account, we need to appeal to more complicated, although still approximate, models. In order to carry our calculations on the basis of these models, it becomes necessary to make some further simplifications. The most extensive results have been obtained on the basis of the model of a self-consistent field[1] and the Hartee-Fock-Slater model.[2] However, the range of applicability of these results has not been studied. Furthermore, in some regions of the thermodynamic variables, in particular, on the lower half-wave of the shock adiabat of aluminum, the results of Refs. 1 and 2 disagree by an amount comparable to the effect itself, as is shown in Fig. 1 in a plot of the pressure P versus the compression $\sigma = \rho/\rho_0$. There is obviously a need for experimental work here.

The possibility in principle of extracting experimental information over the entire range of manifestations of the oscillations on the normal shock adiabats of dense materials was shown in Refs. 5 and 6. However, the large errors in the measurements and in the incorporation of the wave damping make these results useless for refining the theoretical data. For the same reasons, it is not legitimate to attempt to relate gasdynamic measurements with a discussion of shell effects, as in Ref. 7. In an attempt to achieve the accuracy required, we have refined the formulation of the experiments and the experimental procedure. In particular, we use shock waves with a well-defined front shape; the measurements are carried out at eight pressures in a common arrangement; the measurement baseline is reduced; and a new detection method is used.

We studied the shock compressibility of aluminum. We were attracted by the large amplitude of the oscillations on the lower half-wave of the shock adiabat and the need to eliminate the uncertainty in this amplitude. Indications of an anomalous behavior of the properties of lead were found in Ref. 5. For this reason, lead was chosen as a second material for study. We use the conventional layout of the reflection meth-

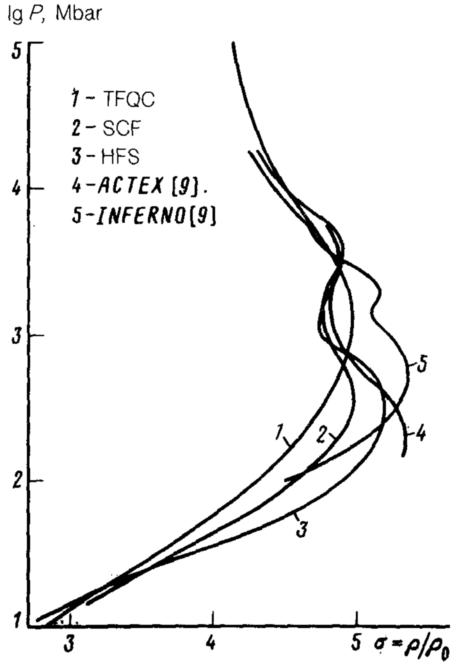

FIG. 1.

od, placing the reference material (iron) first along the path of the front. We selected iron because it has been predicted that shell effects will be slight in iron in the region required for this study. The thickness of the reference layer is 25 mm, and the thicknesses of the layers of aluminum, lead, and iron placed against it are 8, 10, and 12 mm, respectively.

The times at which the front reaches the control surfaces are determined from optical emission of the adjacent layers of air. To achieve the measurement accuracy, we place three control surfaces in the field of view of one of the optical channels. These control surfaces correspond to the selected pressure (two of them to the reference and one to the sample). The mutual illumination is eliminated by the insertion of opaque membranes. All three signals are measured by a common detector. Two detectors are used in each channel to improve the reliability. The complexity of the three-step signal shape mandated the use of an oscilloscope. To improve the accuracy of the time measurements, we use a measurement arrangement in which the working signals are recorded after well-known delays for short intervals.

We directly determined the average wave velocities over the baselines. A conversion was made to the values at the contact boundaries by calculation. The correction amount to 4–8%, depending on the material. The numerical program uses a nonuniform difference method; the front of large jumps is singled out, and the heat-conduction flow regime and the adiabatic flow regime are taken into account. The validity of the corrections is monitored experimentally. Table I shows values of the wave velocity *D* (km/s) at the reference-sample boundaries for each measurement pressure. Also

TABLE I

Iron	Aluminum			Lead		
D	D	P	σ	D	P	σ
88.20 ± 0.7	107.1 ± 0.9	237.9	4.73	76.70 ± 0.7	543.8	5.39
71.25 ± 0.6	85.98 ± 0.8	152.5	4.64	61.33 ± 0.7	346.5	5.31
66.74 ± 0.6	80.11 ± 0.8	132.5	4.66	56.98 ± 0.6	300.2	5.40
62.65 ± 0.6	75.03 ± 0.7	115.9	4.61	53.43 ± 0.6	262.4	5.26
54.90 ± 0.6	65.22 ± 0.6	87.3	4.55	46.60 ± 0.5	197.3	5.00
42.63 ± 0.7	50.58 ± 0.7	50.6	4.05	35.44 ± 0.6	111.6	4.60
41.79 ± 0.6	49.45 ± 0.7	48.5	4.00	35.00 ± 0.6	107.2	4.37
36.77 ± 0.5	43.57 ± 0.6	36.3	3.73	30.42 ± 0.5	79.6	4.13

shown here is the total error (%) corresponding to a confidence level of 0.95. This error is due primarily to the uncertainty in the choice of the reference point for the time measurements; it stems from the finite thickness of the oscilloscope trace.

Also shown in Table I are values of the pressure P (Mbar) and the compression σ on the shock adiabats of aluminum and lead, found from the interpolation equation of state of iron from the data of Refs. 1 and 8. Figures 2 and 3 compare these results with the shock adiabats of Refs. 1 and 8 and the Thomas-Fermi model with quantum corrections. The errors in the values of σ are shown for some of the points. The experiments are seen to agree well with the results of Refs. 1 and 8. If we interpret the results on the basis of Thomas-Fermi model with quantum corrections, we find that the experimental points are displaced upward along the compression scale for alumi-

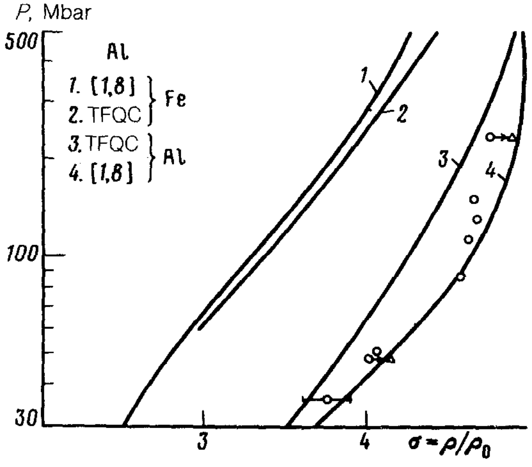

FIG. 2.

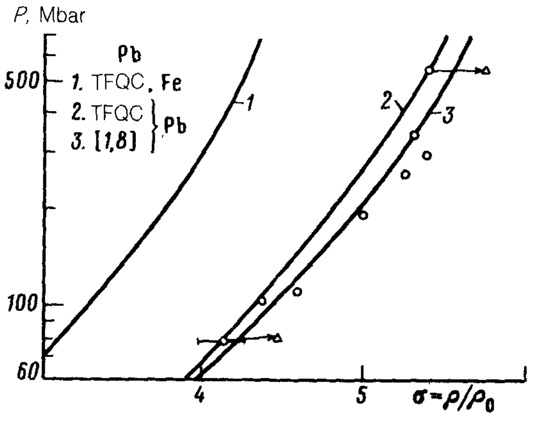

FIG. 3.

num by $\Delta\sigma/\sigma \cong 0.15$ and by $\Delta\sigma/\sigma \cong 0.25$ for lead, for essentially the same position of the shock adiabat of iron. These experimental points also deviate significantly from the corresponding calculated shock adiabats (the displacements of some of the points are shown by arrows in Figs. 2 and 3). This result is evidence of a significant discrepancy between the equations of state of the Thomas-Fermi model with quantum corrections for the reference and for the test samples. This disagreement is also seen in the *D,D* variables. For example, the corresponding results for the aluminum-iron pair constructed from the data of Refs. 1 and 8 and the Thomas-Fermi model with quantum corrections diverge by 1.25–2 km/s in the pressure range studied. This discrepancy is greater than the errors in the data.

The functional relationship between the wave velocities in the reference and in the sample is approximately linear. Consequently, in accordance with a suggestion by N. N. Kalitkin, we can statistically process the entire set of experimental data. This circumstance makes it possible to reduce by a factor ~ 3 the error in the estimate of the amplitude of the lower oscillation in comparison with the error of a single point. The amplitude values agree well with the values found from the equations of state of the type in Refs. 1 and 8, although the half-wave considered may be more compressed along the pressure axis.

[1] G. V. Sin'ko, ChMMSS **12**, 121 (1981).
[2] A. F. Nikiforov, V. G. Novikov, and V. B. Yvarov, Dokl. Akad. Nauk SSSR **267**, 315 (1982) [*sic*].
[3] N. N. Kalitkin, Zh. Eksp. Teor. Fiz. **38**, 1534 (1960) [Sov. Phys. JETP **11**, 1106 (1960)].
[4] V. P. Kopyshev, ChMMSS **8**, 54 (1977).
[5] E. N. Avrorin, B. K. Bodolaga, L. P. Volkov, A. S. Vladimirov, V. A. Simonenko, and B. T. Chernovolyuk, Pis'ma Zh. Eksp. Teor. Fiz. **31**, 727 (1980) [JETP Lett. **31**, 685 (1980)].
[6] A. S. Vladimirov, N. P. Voloshin, V. P. Nogin, A. V. Petrovtsev, and V. A. Simonenko, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 69 (1984) [JETP Lett. **39**, 82 (1984)].
[7] I. Sh. Model', A. T. Narozhnyĭ, A. I. Kharchenko. S. A. Kholin, and V. V. Khrustalev, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 270 (1985) [JETP Lett. **41**, 332 (1985)].
[8] A. T. Sapozhnikov and A. V. Pershina, VANT, Ser. Metodiki e Programmy **4**, 47 (1979).
[9] D. A. Yong, J. K. Wolford, F. J. Robers, and K. S. Holian, Phys. Lett. **108A**, 157 (1985).

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