Shock compressibility of aluminum at $p \gtrsim 1$ Gbar

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Experimental data have been obtained on the shock compressibility of aluminum in the pressure range 0.4–4 Gbar by a reflection method with iron used as a comparison standard. These measurements were carried out to test some theoretical equations of state.

The Thomas-Fermi model[1] and modifications of this model incorporating regular contributions of quantum effects[2,3] (TFQ), the nonideal properties of the ion lattices[4] (TFI), etc., are widely used to study the shock compressibility of substances at high pressures. In several cases, the electronic-shell structure of the atoms significantly affects the shock adiabats of dense substances. This effect is taken into account by laborious quantum-mechanical calculations with simplifications,[5–7] whose effect on the results is usually difficult to evaluate.

The manifestations of shell effects in the shock compressibility of aluminum were calculated in Ref. 6 in the model of a self-consistent field, with an approximate account of the energy bands,[5] and also in Ref. 7, in the Hartree-Fock model, with a local account of exchange effects in the Slater approximation. The shock adiabats found for aluminum in those studies and also from the TFI model are shown in Fig. 1 as a plot of the pressure vs the compressibility $\sigma = \rho/\rho_0$. The initial density is $\rho_0 = 2.71$ g/cm^3. The curves from Refs. 6 and 7 oscillate around the smoother TFI curve. The oscillations are in phase, but the amplitudes of the deviations from the TFI curve for the "lower half-wave" are quite different. We thus turn to the possibility of an experimental study of the shock adiabat of aluminum in the oscillation region.

Experimental data on the shock compressibility of aluminum have been found previously for only the lower part of the oscillation region, at pressures[8–10] $p = 0.01$–0.02 Gbar (1 Gbar $= 10^{15}$ erg/cm^3), where we do not yet see deviations from the "smooth" interpolation equations of state recommended previously (in Ref. 8, for example). The upper limit on the pressure range was raised to ~ 0.1 Gbar in the experiments of Ref. 11, but the large total error made it impossible to refine the position of the shock adiabat. In the present experiments, we have raised the upper limit on the pressure to 4 Gbar, and we have improved the experimental accuracy.

The experiments are carried out in the conventional arrangement for the reflection method, with the comparison material first in the wave path.[12] The comparison material is type 20 steel with $\rho_0 = 7.85$ g/cm^3. This particular material was chosen because the shock adiabats and isentropes of iron deviate only slightly from the predictions of the TFI model in the region of thermodynamic variables required for the analysis. The pressures were raised above those achieved in Ref. 11 by abandoning the "plane geometry."

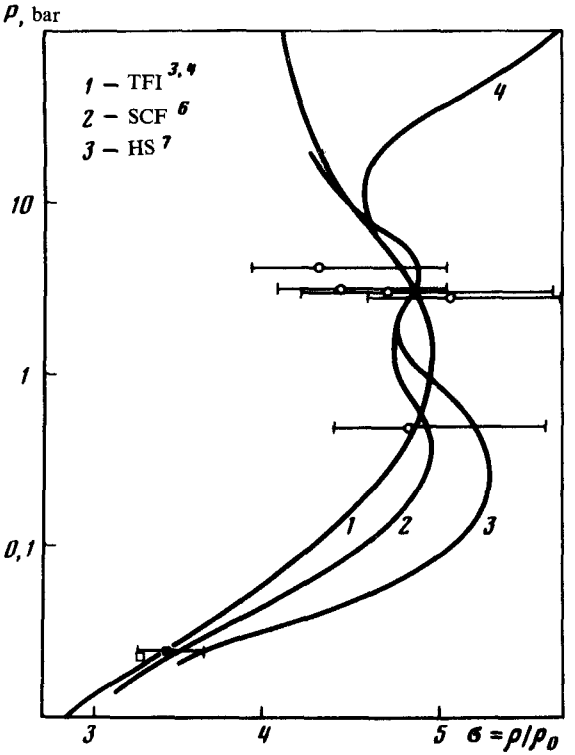

FIG. 1.

We measure the times at which a shock wave reached control surfaces (5–6 such surfaces) in the experimental apparatus. We use the optical emission which appears at the instant of arrival in an air-filled light duct pointed at each control surface. Measures are taken to keep the wavefront very accurately parallel to the control surfaces. The time intervals are measured from a common reference signal. Figure 2 shows some representative oscilloscope traces (1 is the reference signal, and 2 is the light; the time interval between the markers is 0.1 μs). To improve the accuracy of the measurement of the time intervals, we extended the measurement base line to ~ 10 cm. The damping of the shock wave was taken into account by gasdynamic calculations and monitored experimentally. The experimental data on the damping agree well with the theoretical predictions.

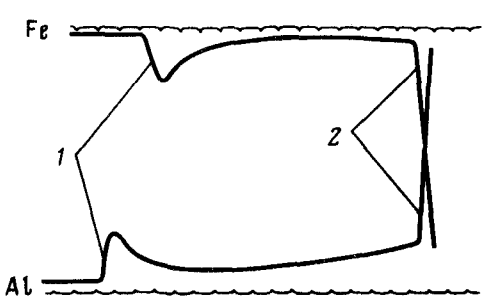

FIG. 2.

TABLE I.

N⁰	Iron			Aluminum		
	D	p	σ	D	p	σ
1	120 ± 2	0.89	4.74	147 ± 2	0.46	4.85
2	286 ± 4	5.16	5.09	353 ± 4	8.71	5.06
3	291 ± 5	5.34	5.09	366 ± 6	2.84	4.71
4	298 ± 4	5.59	5.09	379 ± 5	3.00	4.44
5	344 ± 6	7.47	5.08	441 ± 6	4.04	4.32

Five series of measurements were carried out at various intensities of the wave in the comparison standard. Table I shows the wave velocities D (in kilometers per second), the pressures (gigabars), and the compressibility values at the front found from an analysis of the measurements.

The indicated errors in D correspond to a confidence level of 0.68. These errors are determined primarily by the errors in the measurement of the time interval and by possible errors in the calculations of the wave damping. In the analysis for the comparison material we used the TFI equation of state. The results are shown along with the errors in the compressibility in Fig. 1. Also shown there are data obtained at $p \gtrsim 0.01$ Gbar in other studies. The experimental point denoted by the open square, taken from Ref. 10, is shown along with the value (filled square) found through an analysis by the TFI model. We see that the experimental and theoretical results agree satisfactorily at $p = 0.01$–0.02 Gbar.

These results make it possible to extend the pressure range studied up to values at which the thermal radiation behind the wave-front affects the shock compression (curve 4 in Fig. 1). Experiments have thus now been carried out over the entire range of oscillations on the shock adiabat of aluminum coming from a state with standard initial density. For a test of the theoretical models, however, the accuracy of the measurements by the reflection method must be improved by a factor of three to five. This improvement is technically feasible. It will require using better measurement systems and recorders. We note in conclusion that the pressures achieved in this experiment are the highest which have been achieved to data in shock-wave experiments.

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