RELATIVE COMPRESSIBILITY OF IRON AND LEAD AT PRESSURES OF 31 to 34 MBAR

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The results are given of an experimental determination of high-pressure-shock relative compressibility of iron and lead with the latter used as a standard. The shock wave velocity during its successive passage through layers of iron and lead was determined. The measured values of the wave velocities corresponded to a pressure of 34.4 Mbar in lead, and 31.2 Mbar in iron, and a density of iron of 19.7 g/cm^3.

THE highest pressures and densities in compressed bodies have been reached experimentally by the "deceleration method" in fronts of shock waves generated by the impact of a flying striker against an investigated sample. In this way, using steel strikers traveling at ~8.5 km/sec, shock pressures of ~5 Mbar have been reached in steel, copper, and in other metals of similar dynamic rigidity;[1-3] pressures of ~10 Mbar have been reached using striker velocities of ~14 km/sec.[4-6] Further progress to higher pressures meets with considerable difficulties if absolute measurements are to be carried out, since strikers must be accelerated to still higher velocities.

A different and simpler method is to carry out relative measurements of velocities of very strong shock waves in an investigated substance and in a standard material whose dynamic adiabat can be extrapolated theoretically with a reasonable degree of reliability. The present paper reports the results of the use of this method to determine the position of the shock adiabat of iron at pressures exceeding 30 Mbar. Lead has been used as a standard material; it is an element with a high atomic number and the quantum-statistical approximations for this element are much more reliable for lead than for iron. The higher compressibility of lead also has certain advantages.

To obtain the required information, we measured the velocity of a strong shock wave of a subterranean explosion during its subsequent passage through a layer of iron (soft steel) 120 mm thick and a layer of lead 60 mm thick (Fig. 1a).

In each case, the transit times were determined by several pairs of electrical contacts, which emitted signals (at the moment of closing) that were than applied to the plates of cathode-ray oscillographs. The time intervals recorded with parallel pairs of contacts differed from one another by less than 1%.

The measured values of the wave velocities in steel (D = 26.21 km/sec) and lead (D = 20.50 km/sec), obtained at the midpoints of the measurement bases, are presented graphically in Fig. 1b. After correction for the damping, the wave velocities at the common boundary between steel and lead were: 20.72 km/sec for lead and 25.70 km/sec for steel.

This result is represented by the upper point of the $D_{Pb}(D_{Fe})$ curve, plotted using $D_{Fb} - D_{Fe}$ coordinates in Fig. 2. The same figure includes the data obtained at lower pressures and reported in[2,4,7]. All these points can be approximated by the dependence[1)]

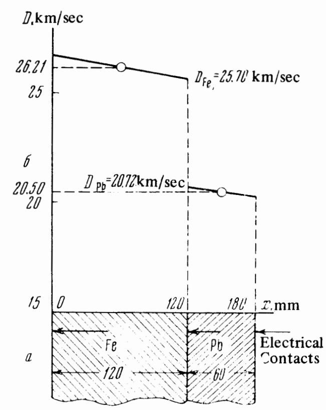

FIG. 1. Experimental arrangement and results of measurements of wave velocities in iron and lead. O – experimental points at midpoints of measurement bases.

$$D_{Pb} = -0.339 + 0.7054\,D_{Fe} + 0.448\cdot 10^{-2}\,D^2_{Fe},$$

represented by the upper curve in Fig. 2. The relationship obtained between the velocities, which covers the range of pressures up to ≈35 Mbar, represents the direct result of our investigation.

Further analysis is based on the use of a standard adiabat of lead, which is given in Fig. 3 on a semilogarithmic scale. The experimental part of the adiabat[2,4,7] is limited to pressures of ≈10 Mbar, while the branch calculated by quantum statistics is limited to minimum pressures of ≈300 Mbar.

In calculating the upper part of the adiabat, the contribution of electrons to the thermal energy and pressure has been allowed for in accordance with[8], the thermal properties of the lattice have been allowed for

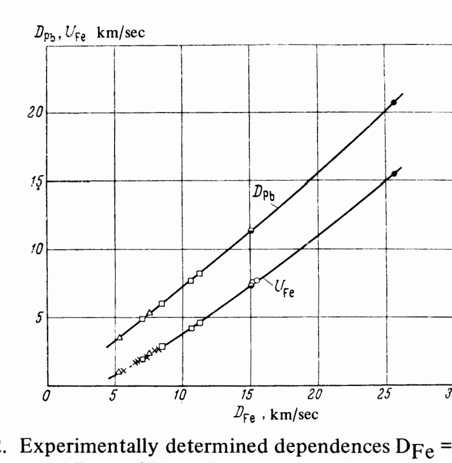

FIG. 2. Experimentally determined dependences $D_{Fe} = f(D_{Pb})$ (upper curve) and $D_{Fe} = f(U_{Fe})$ (lower curve). ● – results of present investigation; Δ – [1]; □ – [2]; ◒ – [4]; O – [5]; X – [7].

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1) Values of the velocities D_{Pb} and D_{Fe} are expressed in km/sec.

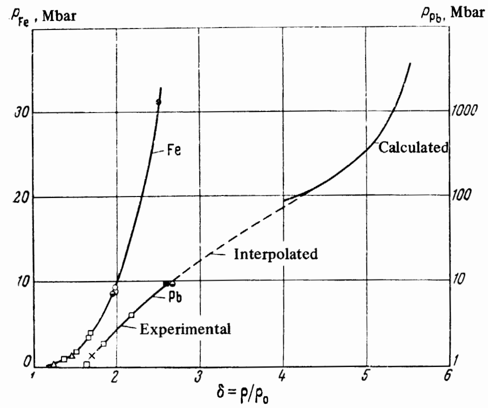


FIG. 3. P – δ diagrams of the standard adiabat of lead and of the experimental adiabat of iron. □ – unpublished results of the present authors. The rest of the notation is the same as in Fig. 2.

Table I. Dynamic Adiabat of Lead

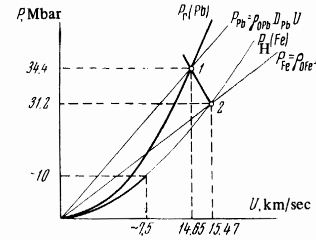
P, Mbar	$\delta = \rho/\rho_0$	U, km/sec	Remarks
5	2.31	5.00	Experiment
10	2.61	7.38	
15	2.96	9.36	Interpolation region
20	3.09	10.92	
25	3.13	12.25	
30	3.32	13.60	
35	3.45	14.80	
40	3.53	15.90	
50	3.66	17.90	
75	3.95	22.23	
100	4.19	25.91	
200	4.70	37.26	
300	4.91	45.90	Quantum-statistical calculation
500	5.11	59.55	
1000	5.32	84.62	

in accordance with [6], and the parameters of the cold compression curve for $\rho > 4\rho_0$ have been taken from [4]. The adiabat at intermediate pressures has been deduced by graphical interpolation. It is assumed that the error in the degree of compression of lead does not exceed $\Delta\delta_{st} = \pm 0.08$ at P = 30–40 Mbar. The results of calculations, as well as the characteristics of the adiabat of lead in the experimental and interpolation regions, are given in Table I. The adiabat of lead is represented schematically by the left-hand curve in the pressure-velocity diagram given in Fig. 4. Its intersection at the point 1 with a wave ray $P = (\rho_{Pb})_0 D_{Pb} U$ ($D_{Pb} = 20.72$ km/sec) gives the parameters of shock-compressed lead listed in Table II.

Below the adiabat of lead lies the part of the shock compression curve of iron up to ≈10 Mbar (found earlier) and a wave ray for iron[2)] $P = (\rho_{Fe})_0 D_{Fe} U$, plotted using the experimental value D_{Fe} = 25.70 km/sec. State 2 of the compressed iron lies on the wave ray and it also represents the branching point of the shock deceleration adiabat of iron, passing through state 1 on the adiabat of lead.

To determine state 2, we have plotted a network of adiabats representing compression to half the volume, associated with different points on the wave ray. The adiabats have been plotted using the equation

FIG. 4. Schematic diagram used to determine the shock-compression parameters of iron



$$P = P_c + \rho_c[C_c + \lambda(U_c - U)] \times (U_c - U).$$

Here

$$P_c = \rho_{0\,Fe} D_{Fe} U_c,\quad \rho_c = \rho_{Fe} D_{Fe} (D_{Fe} - U_c)^{-1},$$

U_c is the abscissa of the selected point on the wave ray; λ is a parameter close to unity (its influence on the nature of the adiabat of iron near state 1 is negligibly small); C_c is the velocity of sound in iron, which determines, through the equation $(\partial P/\partial U)_c = \rho_c C_c$, the slope of the adiabat of iron at its branching point. According to [9], $C_c = 0.85D$ at $P \approx 4$ Mbar. In the far extrapolation region, $C_c = 0.5D$. In accordance with estimates deduced from the equation of state of iron,[4] we shall assume that $C_c = 0.8D$. We must mention that in view of the similarity of the adiabats of iron and lead, the final results are not affected by possible variations in the value of C_c.

The deceleration adiabat passing through state 1, is shown by curve 2–1 in Fig. 4. The coordinates of point 2 determine the parameters of iron compressed by a shock wave passing through it (Table II).

In estimating the accuracy of the results obtained, we must take into account the error in the standard adiabat ($\Delta\delta_{st} = \pm 0.08$) and the inaccuracies $\Delta D/D$ in the experimental measurements of the wave velocities, amounting to ±0.7%. According to an easily deduced relationship, the relative error in the determination of the density of iron is

$$\frac{\Delta\rho}{\rho} = \pm(\delta_{Fe} - 1)\left\{\left[\frac{\Delta\delta_{st}}{\delta_{st}(\delta_{st} - 1)}\right]^2 + \left(\frac{\Delta D}{D}\right)^2_{Fe} + \left(\frac{\Delta D}{D}\right)^2_{Pb}\right\}^{1/2} = \pm 2\%.$$

It follows from the above expression that the error in the determination of the density depends strongly on the degree of compression of the standard substance and that it decreases when δ_{st} increases. As already pointed out, this circumstance has been one of the reasons guiding us in the selection of lead as the standard substance.

The left-hand part of Fig. 3 shows in the coordinates p–δ, the adiabat of iron up to pressures of ≈32 Mbar, and the same adiabat is presented in Fig. 2 in the coordinates D–U. The application of shock pressures of ≈31 Mbar increases the density of iron by a factor

Table II. Parameters of Shock Waves in Lead and Iron (at the iron-lead boundary)

Metal	D, km/sec	U km/sec	P, Mbar	g/cm³	δ
Pb, $\rho_0 = 11.34$ g/cm³ (State 1)	20.72	14.65	34.4	38.7	3.41
Fe, $\rho_0 = 7.85$ g/cm³ (State 2)	25.70	15.47	31.20	19.7	2.51

2) Here and later, we shall make no distinction between shock adiabats of soft steel and iron.

of 2.51, i.e., up to ≈19.7 G/cm^3. The specific compression energy, accumulated by iron is very high: ≈120 kJ. This energy is ≈30 times higher than the explosive energy of 1 g of trotyl. About 90% of this energy is in the form of the thermal motion of ions and electrons in the metal, the thermal motion of the electrons being the dominant effect. The thermal pressure, equal to 19 Mbar, exceeds by a factor of about 1.5 the resistance offered by a cold metal to the forces causing an increase in its density. The contribution of electrons to the thermal motion is equivalent to ≈14 Mbar. These estimates of the components of the energy and pressure are deduced by slight extrapolation of cold-compression curves of iron taken from [4] and from calculations, using the Gandel'man method,[10] of the thermodynamic properties of the electron gas.

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