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RELATIVE COMPRESSIBILITY OF COPPER, CADMIUM, AND LEAD AT HIGH PRESSURES

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The results are reported of measurements of the comparative compressibility of copper, cadmium, and lead at pressures up to 15 Mbar. The following densities were reached at these pressures: 19.97 g/cm^3 for copper, 22.77 g/cm^3 for cadmium, and 33.61 g/cm^3 for lead.

EXPERIMENTAL information at very high pressures is now obtained using strong shock waves. Determination of the absolute values of the pressure and shock-compressed density requires, as reported in[1-3], independent recording of two parameters: the shock-wave velocity and the mass velocity of matter behind the shock-wave front. At high shock-wave amplitudes, the second parameter is found from the velocity of a striker which produces a shock wave in the target (sample). At the currently achievable striker velocities of ~14 km/sec, the range of absolute measurements is limited to pressures of ~10 Mbar.

The use of the reflection method[1] to carry out comparative measurements avoids the difficulties associated with the requirement of highly symmetrical acceleration of strikers to high velocities without causing any heating. This makes it much easier to reach the range of extremely high pressures and to obtain, using very strong shock waves,[4] information on the relative compressibility of various materials at pressures of a few tens of megabars.

The reflection method is based on recording the velocities of a shock wave as it passes through layers of the investigated substances. One of these substances is used as a standard. The present paper reports the results of measurements of the relative compressibility of lead, copper, and cadmium at pressures of ~15 Mbar. We determined experimentally the velocity of a shock wave during its passage through layers of lead (70 mm thick), copper (80 mm), and cadmium (70 mm), as shown in Fig. 1.

The motion of a shock wave was recorded by four groups of electric-contact pickups, whose signals were applied to the plates of cathode-ray oscillographs with a driven sweep. The high symmetry of the motion of the shock wave and fairly large thicknesses of the investigated samples made it possible to record, with a given accuracy, the wave velocities in the investigated metals. The time intervals, recorded by pairs of contacts, located along different diameters, differed by not more than 0.5%.

The direct results of experimental determinations of wave velocities are presented in Fig. 1. After the reduction of these values to the boundary conditions between different metals (using a calculated law of attenuation of shock waves), the wave velocities were found to be (D in km/sec):

Pb-Cu boundary: $D_{\mathrm{Pb}}=14.64$, $D_{\mathrm{Cu}}=17.82$
Cu-Cd boundary: $D_{\mathrm{Cu}}=17.47$, $D_{\mathrm{Cd}}=16.08$

Following Al'tshuler et al.,[4] we used lead as the

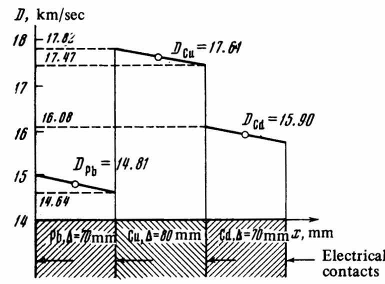

FIG. 1. Schematic representation of the samples and the results of measurements of the wave velocities (in km/sec) in lead, copper, and cadmium. O represents experimental points.

standard substance, and we obtained its dynamic adiabat at $\gtrsim$ 10 Mbar by graphical extrapolation into the range of theoretical solutions. According to our estimates the indeterminacy of the position of the adiabat along the density axis at P ~ 15 Mbar was $\Delta\sigma = \pm 0.04$ (where $\sigma = \rho/\rho_0$, ρ is the density of the compressed metal, and ρ_0 is the initial density). The part of the dynamic adiabat, extrapolated in accordance with[4] to ~20 Mbar, was described by the following equation in the P-σ coordinates:

$$P = \frac{\rho_0 C_0'^2}{(\lambda-1)^2} \frac{\sigma(\sigma-1)}{[\lambda/(\lambda-1)-\sigma]^2},$$

where $C_0' = 2.81$ km/sec, $\lambda = 1.222$, 4 Mbar $\le P \le$ 20 Mbar.

The subsequent interpretation of the results was based on the usual plots[1-3] in the pressure-mass velocity diagram (Fig. 2). The initial state of the standard was found in this diagram from the intersection of the wave ray $P = \rho_{0\,\mathrm{Pb}} D_{\mathrm{Pb}} U$ (D_{Pb} = 14.64 km/sec) with the interpolated dynamic adiabat of lead. The state of copper was determined from the intersection of the wave ray of copper $P = \rho_{0\,\mathrm{Cu}} D_{\mathrm{Cu}} U$ (D_{Cu} = 17.82 km/sec) with a segment of the mirror image of the dynamic adiabat of lead. The procedure for the copper-cadmium pair was similar. The parameters of the experimental points are given below:

	D, km/sec	U, km/sec	P, Mbar	σ	ρ, g/cm^3
Cu, $\rho_0 = 8.93$ g/cm^3:	17.82	9.85	15.69	2.236	19.97
Cd, $\rho_0 = 8.64$ g/cm^3:	16.08	9.98	13.87	2.635	22.77

The initial states of the screens were as follows: in the first case (lead screen):

$D_{\mathrm{Pb}} = 14.64$ km/sec, $U_{\mathrm{Pb}} = 9.70$ km/sec, $P_{\mathrm{Pb}} = 16.1$ Mbar;

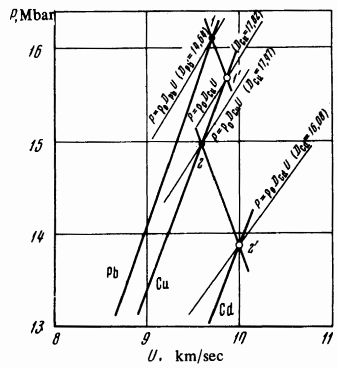

FIG. 2. Determination of the shock-compression parameters of copper and cadmium by the reflection method. ●: 1), 2) Initial states of shock-compressed lead and copper samples; 1–1′), 2–2′) expansion curves of lead and copper. ○: 1′), 2′) shock-compressed states of copper and cadmium (D in km/sec).

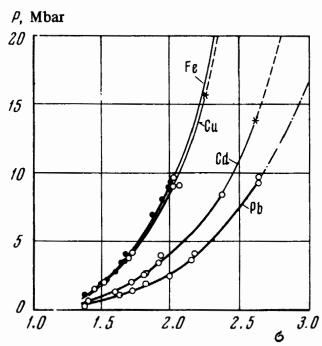

FIG. 3. Shock adiabats of copper, cadmium, lead, and iron at pressures up to 20 Mbar: * – our results; ○, ●, and thick lines – absolute values of the dynamic compressibility taken from [1-3, 5]; thin continuous lines – relative compressibilities of metals (the shock adiabat of iron is taken from [4]); chain curve – interpolated adiabat of lead according to [4]; dashed curves are the extrapolated parts of the dynamic adiabats of copper and cadmium.

in the second case (copper screen):

$$D_{Cu} = 17.47\ \text{km/sec},\ U_{Cu} = 9.58\ \text{km/sec},\ P_{Cu} = 14.95\ \text{Mbar}.$$

The accuracy of the obtained results was governed by the error in the lead adiabat and by the experimental errors $\Delta D/D$ in the determination of the wave velocities. According to[4]:

$$\frac{\Delta\rho}{\rho} = \pm(\sigma - 1)\left\{\left[\frac{\Delta\sigma_{\text{stand}}}{\sigma_{\text{stand}}(\sigma_{\text{stand}} - 1)}\right]^2 + \left(\frac{\Delta D}{D}\right)^2 + \left(\frac{\Delta D}{D}\right)^2_{\text{stand}}\right\}^{1/2}$$

($\sigma = \rho/\rho_0$). For copper, we found that $\Delta\rho/\rho = \pm 0.02$ and for cadmium, $\Delta\rho/\rho = \pm 0.03$.

Figure 3 compares the results obtained, presented in the pressure-relative compression coordinates, with the absolute measurements of the shock compressibility of copper and cadmium reported in[1,2,5]. Compared with[2], the range of pressures investigated in the present study was ~1.73 times greater for copper and ~1.65 times greater for cadmium. The shock compression reached in our study was approximately 11% higher than the corresponding values reported in[2]. The same diagram includes the shock adiabats of iron and lead taken from[2,3,5]. It is evident from the figure that the compressibility of the four elements being compared is very different. The steepest adiabats are those of iron and copper, which are elements with relatively small initial atomic volumes and large binding energies. The highest compressibility is exhibited by lead. The cadmium adiabat occupies an intermediate position between lead and copper or iron.

At pressures of 20 Mbar, the densities of iron, copper, cadmium, and lead increased by a factor of 2.32, 2.34, 2.80, and 3.11, respectively; the specific energies of shock compression were 72, 64, 74, and 60 kJ/g, respectively.

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135