Compressibility of iron, aluminum, molybdenum, titanium, and tantalum at shock-wave pressures of 1–2.5 TPa

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The compressibility of five metals at pressures of 1.0 (aluminum) to 2.5 (tantalum) TPa was investigated under laboratory conditions. The pressures were produced by the impact of a hemispherical steel shell, which was accelerated to velocities of 23 km/s by the explosion products of a converging detonation wave, against the samples. The experimental data are compared with the results obtained with strong shock waves from underground nuclear explosions. © *1995 American Institute of Physics.*

A possibility of performing measurements of the compressibility of materials under conditions of strong shock waves with amplitudes $>1-2$ TPa has been lost now that underground nuclear explosions are no longer allowed. Existing laboratory setups for explosive testing[1] are limited to pressures $P \leqslant 1$ TPa (for substances with initial density $\rho \approx 8.0$ g/cm^3). Even ignoring the general interest in extending measurements to ultrahigh pressures, after the moratorium on underground tests was instituted, some problems whose resolution required tests at terapascal pressures remained unresolved. Specifically, they included inconsistencies in the compressibility data for molybdenum (at $P \approx 2$ TPa), the need for direct comparison of laboratory and "underground" data on aluminum at $P \approx 1$ TPa, and some others. To solve these problems under laboratory conditions, it was necessary to have a setup that makes it possible to perform compressibility measurements at such pressures. Such a setup was developed — see Ref. 2 , where the results of measurements of the compressibility of tantalum at pressures $P \approx 1.7$ TPa were published. The measurements were performed under conditions where the high pressures were produced by the impact of a steel shell accelerated by the explosion products of a converging detonation wave against the measurement core, positioned near the center of the system, which contained metal samples.

The pressures produced in that experiment[2] were record-high for laboratory conditions. However, even those pressures did not allow a direct comparison of the aluminum and molybdenum data, which required an apparatus that produced pressures of up to 2 TPa. To achieve such conditions, it was decided to use the apparatus of Ref. 2 in the forced mode. The measuring core with the metal samples was positioned closer to the center of the system at the minimum radius, where measurements of the wave velocities can still be performed with the required measurement accuracy. We are talking here about measurements of the absolute, in the methodological sense, compressibility of materials, i.e., a situation in which the thermodynamic quantities characterizing the state of the experimental material, such as the pressure and density of shock compression, are determined directly in terms of experimentally determined kinematic parameters — the wave and mass velocity.

As usual in such cases, the velocity of the shock wave produced in the experimental metal samples by the impact of a steel shell accelerated to a velocity $W \simeq 23$ km/s by the explosion products of a converging detonation wave was recorded in the experiments. The samples consisted of hemispherical pellets — 9 mm in diameter and 3.5-mm- thick segments — covered at the top with a steel hemispherical screen of the same thickness. We used an electrocontact recording system which recorded the transit time of the shock wave through the samples on SUPI-type recorders, with the error in reading of the oscillograms 5×10^{-9} s or better.

In the apparatus employed by us, as the shell approaches the screen, there arises in the screen, besides a powerful main shock wave, a relatively weak shock wave (produced by the compressed air "cushion" moving in front of the shell), which leads the main shock front. To prevent preshorting of the upper-level contacts by this leading wave, a 0.3-mm-thick air gap was inserted between the contacts and the screen; this air gap "quenched" the first wave without appreciably affecting the front of the main wave.

In each experiment three samples of different metals were inserted. In most cases iron was present among the samples. The average wave velocities obtained in the experiments, taking into account the small (less than 1%) corrections for the different damping of the waves in the metals as compared with iron, are as follows: iron (reference metal) — $D = 20.19 \pm 0.25$ km/s, aluminum — $D = 24.17 \pm 0.40$ km/s, tantalum — $D = 15.85 \pm 0.20$ km/s, titanium — $D = 20.95 \pm 0.40$ km/s, molybdenum — $D = 18.74 \pm 0.40$ km/s.

The rest of the procedure for analyzing the results is as follows: The initial states in iron — $U = 11.54$ km/s and $P = 1.83$ TPa — are found from the experimental wave velocity in iron and the known $D - U$ relation for iron (U is the mass velocity of the material behind the shock front): $D = 5.68 \pm 1.257 \cdot U$ (the initial density of iron is $\rho_0 = 7.85$ g/cm^3), which is valid in the range 13 km/s $< U < 25$ km/s. Next, we determined the compression parameters of the experimental metals from the wave velocities in them by constructing the $P - U$ diagram. In the case at hand the results are as follows:

aluminum

$U = 15.08$ km/s, $P = 0.99$ TPa, $\rho = 2.71$ g/cm^3 ($\rho_0 = 2.71$ g/cm^3);

tantalum

$U = 9.36$ km/s, $P = 2.47$ TPa, $\rho = 40.00$ g/cm^3 ($\rho_0 = 16.38$ g/cm^3);

titanium

$U = 13.67$ km/s, $P = 1.29$ TPa, $\rho = 12.95$ g/cm^3 ($\rho_0 = 4.5$ g/cm^3);

molybdenum

$U = 10.74$ km/s, $P = 2.05$ TPa, $\rho = 17.80$ g/cm^3 ($\rho_0 = 10.2$ g/cm^3).

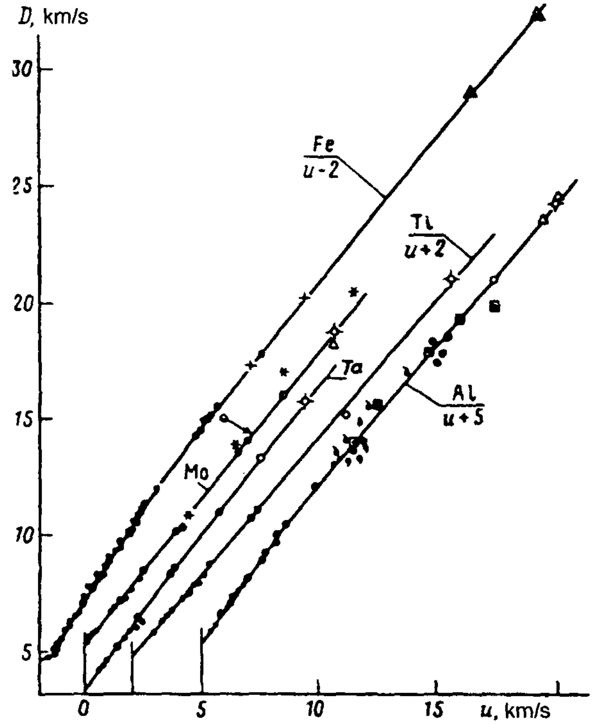

FIG. 1. Shock adiabats of iron, molybdenum, tantalum, titanium, and aluminum. Laboratory measurements: +, ○ — initial states in iron and corresponding data for metals (this work); ○, ▽, ●, ·, · — results from Refs. 2 , 13 , 1 (12), 14 , 15 , respectively; measurements with underground nuclear explosions: ▽, *, △, ⊖, △, □, ⊕ — data from Refs. 10 , 9 , 3 , 4 , 6 , 7 , and 8 , respectively.

In Fig. 1 they are compared with the existing results[1,3-14] obtained under laboratory conditions and with underground nuclear explosions.

What conclusions can be drawn from these data?

For aluminum. The new experimental point is virtually identical with the measurements from Ref. 6 performed with underground explosions. Therefore, both results can be regarded as being consistent with one another. This eliminates the question of the validity of the assumption, made in Ref. 6, that the velocity of the reference pellets mounted in the experimental block is equal to the mass velocity in aluminum.

For titanium. The new measurements confirmed the previously adopted[15] relation D_{Fe}(screen)–D_{Ti} . This had to be done, since in this dependence, which consists of two intersecting straight lines with different slopes, the point of intersection and the slope of the second section were determined by analogy with the dependences for other pairs of metals and required direct experimental confirmation. The data obtained in the present work refer to the region of states which are characteristic of the second section of the D–D diagrams and show that the interpretation adopted in Ref. 15 for the results is correct.

For molybdenum. The data from underground tests[3-5,9] differ strongly from one another: In Ref. 3, the measurements lie below the linear $D-U$ relation, continued from the laboratory region to the region of states characteristic of underground explosions, whereas in Refs. 4 and 9 the measurements lie above this line. The data of Ref. 5 fall between these two measurements, but, unfortunately, the parameters obtained there were not much greater than the laboratory range of the measurements. The new point, which lies at similar pressures, just as the measurements in Refs. 3 , 4 , and 10 , confirms the linearity of the $D-U$ dependence obtained in Refs. 11 and 5 for molybdenum and indicates that the results obtained in Refs. 3 , 4 , and 9 are wrong.

For tantalum. The purpose of the measurements was to study the compressibility of tantalum at higher pressures than those achieved in Ref. 11 . The pressures of up to 2.4 TPa obtained in this work are record-high pressures for laboratory measurements.

In summary, data on the absolute compressibility of tantalum, molybdenum, titanium, and aluminum at pressures more than two times higher than the pressures heretofore achieved under laboratory conditions for these metals were obtained under the conditions of a laboratory experiment. The measurements made it possible to determine more accurately the position of the shock adiabats of these metals at ultrahigh pressures and to solve the remaining problems concerning the interpretation of the data obtained for aluminum, molybdenum, and titanium under the conditions of underground nuclear explosions.

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