Measurement of the compressibility of iron at 5.5 TPa

R. F. Trunin, M. A. Podurets, L. V. Popov, V. N. Zubarev, A. A. Bakanova, V. M. Ktitorov, A. G. Sevast'yanov, G. V. Simakov, and I. P. Dudoladov

(Received 31 March 1992)
Zh. Eksp. Teor. Fiz. **102**, 1433–1438 (October 1992)

The results of measurements of the shock compressibility of iron under pressures of 5.5 TPa are presented. The measurements were performed by the deceleration method—by recording the velocity of a steel striker plate and the velocity of the shock wave in the iron core. The shock wave was produced by an underground nuclear explosion.

In the last three decades, in connection with underground tests of nuclear explosives, the energy of nuclear explosions has been used in many cases for investigating equations of state at ultrahigh pressures which are inaccessible in the laboratory.

In most of these works[1–4] the compressibility was determined by a comparatively simple method (Ref. 1). In this method the parameters of compression of one material were determined with respect to another material, used as a standard, whose equation of state is known.

In order to implement the method it is sufficient to measure the velocity of the shock wave (D) passing successively through the layers of the standard and experimental materials. Further interpretation of the desired states is accomplished by making corresponding constructions on the diagram of the pressure (P) versus the mass velocity (U) of the material behind the shock wavefront, using the method of reflection.[5]

The comparative compressibility has been investigated for a number of classes of materials, including metals and chemical compounds. In Ref. 6 data on the compressibility of the system Fe–Al under gigantic pressures of 75 TPa (Fe) were obtained by this method. Nonetheless, in spite of the obvious successes achieved in these works, investigators were always faced with the question of performing measurements of the compressibility by absolute methods, i.e., determining any two independent parameters (for example, D and U) which relate, through conservation laws, the basic thermodynamic quantities: pressure, density (compression), and energy. In solving this question, even for some one metal standard, all previous comparative measurements can be corrected according to its results.

We have made repeated attempts to determine the absolute compressibility of some standard (Al, Fe) using the so-called method of deceleration.[7] For a number of reasons, these measurements were unsuccessful (or considered to be so). This was explained, in particular, by difficulties in obtaining good symmetry of the travel of the striker plate, developing a "nonheating" system for accelerating the striker plate (we recall that we are talking about terapascal pressures), use of radiation-resistant pickups, etc.

Simultaneously with this classical method for measuring the absolute compressibility, other possible methods, associated with the specific nature of underground explosions—powerful flux of n or γ radiations, for performing absolute measurements were also examined.

In 1977 there appeared a publication[8] in which data were presented on the determination of the absolute compressibility of Mo at pressures of ~ 2 TPa. The mass-velocity measurements were performed on the basis of the shift of the resonances of the interaction of neutrons with the nuclei of the matter with respect to the position of these resonances in nuclei at rest—the so-called Doppler shift. The velocity of the shock wave through the sample was determined by recording the light flashes at the surfaces of the sample. The pressure was produced by uranium-235 fission induced by neutrons from a nuclear explosion.

In 1980 the results of a determination of the absolute compressibility of aluminum by the so-called γ-reference method were published in Ref. 9. In this method the wave and mass velocities are measured simultaneously with the help of special reference tablets which are γ-activated by neutron fluxes from a nuclear explosion and are inserted into the experimental material. The γ bursts produced as the references pass the projections of the collimating slits, arranged on the fixed base thicknesses of the sample perpendicular to the direction of motion of the references, were recorded. In order to find the mass velocities the reference must "pass" through two collimating slits. In Ref. 9 the compressibility of aluminum at pressures of ~ 1 TPa was measured by this method.

Velocities in molybdenum were not recorded accurately enough ($\pm 5\%$; Ref. 8) for use in calibration. The situation is somewhat better in the case of Al,[9] but here the pressures investigated are not much higher than laboratory pressures.

Returning to the analysis of our previous measurements of the absolute compressibility of iron and aluminum (1970–1975) under the conditions of underground tests of nuclear explosives, we called attention to the fact that some of the experiments performed at that time were, in our opinion, no less accurate than the data published in Refs. 8 and 9. For this reason we decided to publish some of the results obtained during those years, especially since now and, apparently, in the next few years it will hardly be possible to obtain more reliable data.

We present below the results obtained in 1974 on the measurement of the absolute compressibility of iron by the deceleration method.

EXPERIMENTAL ARRANGEMENT. SYSTEM CHOICE BASED ON CALCULATIONS

A special system for achieving quite smooth acceleration of the striker was employed in the measurements. A schematic of the system is shown in Fig. 1a. Electric-contact

 0038-5646/92/100777-04$05.00 © 1992 American Institute of Physics

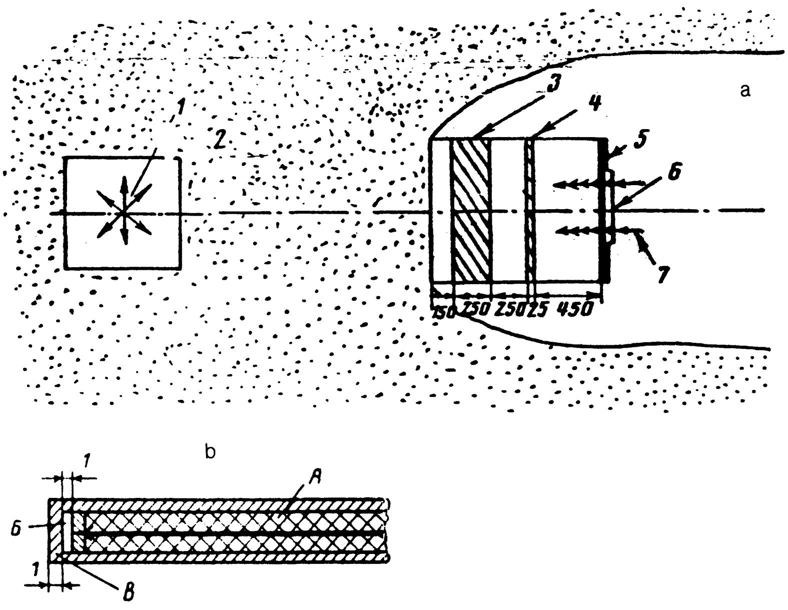

FIG. 1. a: 1—energy source; 2—rock; 3—polystyrene foam; 4—striker, Fe; 5—screen, Fe; 6—target, Fe; 7—electronic pickups; b: A—insulator, B—air gap, C—screen (steel).

pickups, shown schematically in Fig. 1b, were employed as time markers. The velocities were recorded on a finite 150-mm run of a steel plate, where the velocity of the plate was nearly constant. The signals were recorded on IV-30 and IV-36 oscillographs. The time intervals were measured with an accuracy of $\pm$ 5 and 10 nsec, respectively.

The acceleration systems are required to satisfy the following requirements:

1. The striker must accelerate smoothly and it must not heat up much.

2. The striker must reach a constant velocity W before reaching the target.

3. At the moment of impact the plate velocity must equal, with the required accuracy, twice the mass velocity of the shock wave in the target: $W = 2U$.

4. The plate must remain whole and symmetric during its flight.

A system satisfying these conditions was chosen with the help of numerical computational methods. The complete arrangement of the entire experiment—from the nuclear explosion to the completion of the operation of the measuring system under consideration—was taken into account in the calculations.

We note that the equality $W = 2U$ can be strictly satisfied only if the striker plate accelerates smoothly without being heated up and remains whole. In reality, deviations from this equality, which are associated with heating and "expediting" the striker by the pressure exerted by the vaporized material from the rear, and with some other factors, occur. In particular, as the plate is heated by shock waves and is subsequently relaxed to zero pressure, $\rho_{0\,\text{plate}} < \rho_{0\,\text{target}}$. Under actual experimental conditions, however, the density of the plate at the moment of impact can be somewhat higher than $\rho_{0\,\text{target}}$, since in the process of acceleration the plate is expedited from the rear by the "products of the explosion." It is virtually impossible to eliminate this pressure and this factor must simply be tolerated. Other factors which cause W to deviate from $2U$ are also difficult to take into account.

For this reason the choice of the acceleration system must ensure that the equality $W = 2U(\bar{D})$, where $\bar{D}$ is the average velocity of the shock wave in the target, is satisfied as accurately as possible. The velocities $\bar{D}$ and W are experimentally determined quantities; the function $U(D)$ corresponds to the equation of state employed for iron in the calculation.

The system presented in Fig. 1a corresponds to one of the optimal computational variants of the problem with the chosen energy of the explosion. It was calculated using the equations of state with the limiting density;[10] for foamed polystyrene the equation of state corresponded to an ideal gas with the ratio of specific heats $\gamma = 5/3$ ($\rho_0 \simeq 0.03$ g/cm^3). The basic characteristics obtained in the calculations are as follows: the amplitude of the first shock wave in the accelerated steel plate $P_{1\text{Fe}} \lesssim 0.5$ TPa and the average density of the plate at impact was equal to $1.05\rho_0$.

A plot of the velocity of the front surface of the plate as a function of distance is presented in Fig. 2. On the initial section of acceleration the velocity of the plate changes suddenly (the jumps occur with the waves reflected from the back side reach the inner surface); at the end of the motion (before the collision with the target) the velocity increases continuously, reaching the regime $W =$ const. In the target $D_{\text{calc}} = 29.1$ km/s, which corresponds to $U(D) = 18.1$ km/s. The plate approaches the target at a velocity $W = 36.32$ km/s (the velocity of the back side of the plate is $W = 36.18$ km/s). Thus a correspondence $W = 2U(D)$ was obtained in the calculation, i.e., the experimental system was chosen so that there is virtually no correction for the fact that W differs from $2U$ (on the shock front), and for comparatively small discrepancies between the experimental data and the calculations the correction can be neglected.

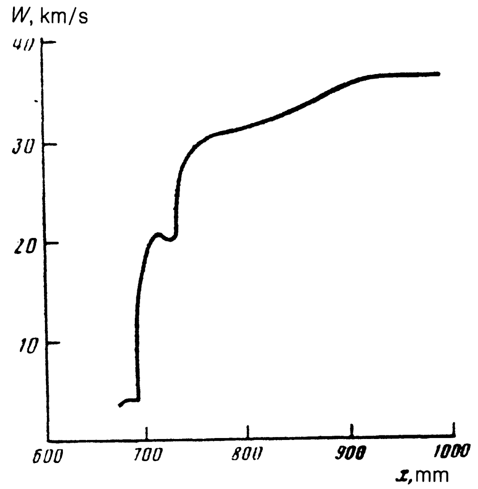

FIG. 2.

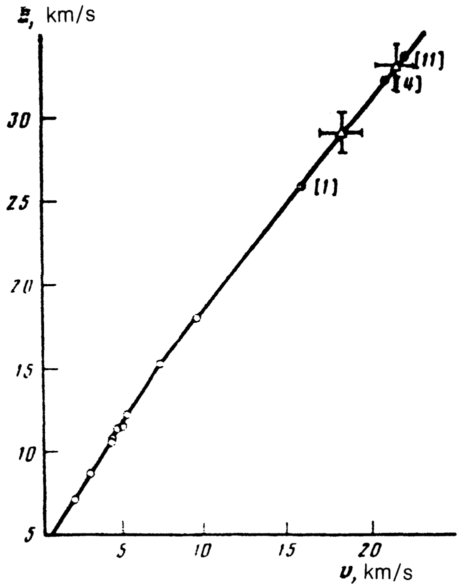

FIG. 4. D–U diagram of iron. Δ—new experimental point (absolute method); ○—laboratory data; ●—"underground measurements" (comparative method).

EXPERIMENTAL DATA

The results obtained are presented in t-x (time-path) coordinates in Fig. 3. They can be represented by two average straight lines of different slope. The spread in the triggering of separate pickups (especially for W) is very significant. This probably indicates that the motion of the striker is somewhat asymmetric. Unfortunately, not all data produced by the electric-contact pickups were obtained in the experiments, and this made it somewhat more difficult to interpret the results. In the final analysis, however, it was found that the interpretation is quite close and the proposed variants do not differ much, so that the estimates of the position of the experimental point obtained on the shock adiabat of iron are quite reliable. In the final variant the velocity with which the plates approach the target was determined as the average value from three groups of electric pickups. The average value was $W = 36.50 \pm 2.0$ km/s (separate groups (blocks) of contacts give the following values for W: 33.7, 35.2, and 40.8 km/s). The average velocity of the shock wave in the target is equal to $D_{\mathrm{Fe}} = 28.85$ km/s.

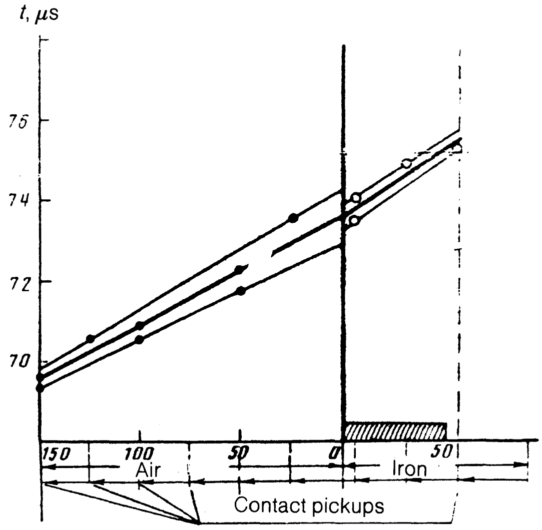

FIG. 3. t–x diagram of the flight of the striker plate and the shock wave in the target. ○, ●—experimental recordings of the wave velocity in the target and the flight velocity of the plate, respectively. The thick line is the average dependence.

Thus the following parameters of an experimental point on the shock adiabat of iron were obtained:

$$D = 28.85 \text{ km/s}, \ U = 18.25 \text{ km/s},$$

$$P = 4.13 \text{ TPa}, \rho = 21.36 \text{ g/cm}^{13}, \sigma = 2.72 .$$

The fact that the plots of the motion of the plate and the shock wave in the target agree at the boundary of the sample confirms that the results are reliable. This agreement indicates that the results obtained are internally consistent (see Fig. 3).[1)]

In Fig. 4 the experimental point in D–U coordinates is compared with the data obtained in Refs. 1, 4, 11 on the comparative compressibility of iron in approximately the same range of measurements. Both forms of information—data on the comparative compressibility and the absolute measurements—agree with one another.

Thus we can state that the data presented show that there are no significant errors in the position of the shock adiabat obtained for iron in this pressure range from comparative measurements.

[1)]After this paper was prepared for publication, we analyzed the results of a new experiment on the determination of the absolute compressibility of iron (the experiment itself was performed in 1971). The experimental arrangement was close to the arrangement considered in the present work. The following results were obtained: $D = 32.36 \pm 0.5$ km/s, $W = 42.74 \pm 0.6$ km/s ($U = 21.37$ km/s), $P = 5.43$ TPa, $\sigma = 2.944$ ($\rho = 23.11$ g/cm^3). The relative positions of the experimental points agree well with one another.

[1]L. V. Al'tshuler, B. N. Moiseev, L. P. Popov, G. V. Simakov, and R. F. Trunin, Zh. Eksp. Teor. Fiz. **54**, 785 (1968) [Sov. Phys. JETP **27**, 420 (1968)].
[2]R. F. Trunin, M. A. Podurets, B. N. Moiseev, G. V. Simakov, and L. V. Popov, Zh. Eksp. Teor. Fiz. **56**, 1172 (1969) [Sov. Phys. JETP **29**, 630 (1969)].
[3]R. F. Trunin, G. V. Simakov, M. A. Podurets, B. N. Moiseev, and L. V. Popov, Izv. Akad. Nauk SSSR, Fiz. Zemli **1**, 13 (1971).
[4]R. F. Trunin, M. A. Podurets, G. V. Simakov, L. V. Popov, and B. N. Moiseev, Zh. Eksp. Teor. Fiz. **62**, 1043 (1972) [Sov. Phys. JETP **35**, 550 (1972)].

[5]L. V. Al'tshuler, K. K. Krupnikov, and M. I. Brazhnik, Zh. Eksp. Teor. Fiz. **34**, 886 (1950) [Sov. Phys. JETP **7**, 614 (1958)].
[6]E. N. Avronin, B. K. Vodolaga, N. P. Voloshin *et al.*, Zh. Eksp. Teor. Fiz. **93**, 613 (1987) [JETP **66**, 347 (1987)].
[7]L. V. Al'tshuler, K. K. Krupnikov, B. N. Ledenev, V. I. Zhuchikhin, and M. I. Brazhnik, Zh. Eksp. Teor. Fiz. **34**, 874 (1958) [Sov. Phys. JETP **7**, 606 (1958)].
[8]C. E. Ragan III, M. G. Silbert, and B. C. Diven, J. Appl. Phys. **48**, 2860 (1977).
[9]L. P. Volkov, N. P. Voloshin, A. S. Vladimirov, V. N. Nogin, and V. A. Simmonenko, Pis'ma Zh. Eksp. Teor. Fiz. **31**, 623 (1980) [JETP Lett. **31**, 588 (1980)].
[10]Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* [in Russian], Nauka, Moscow, 1966.
[11]C. E. Ragan III, Phys. Rev. A **29**, 1391 (1984).

Translated by M. E. Alferieff