Shock compressibility of aluminum at a pressure of 10 Mbar

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A method is proposed for measuring the phase and mass velocity of a shock wave by recording the motion of the γ-reference point located in the investigated material. The measurement device is irradiated by a neutron flux. A thin layer containing atoms of an isotope with a large radiation capture reaction cross section serves as the γ-quanta source. In contrast to the reflection method, the proposed procedure makes it possible at high pressures to obtain independent information about the shock compressibility of materials. Experimental data on the shock compressibility of aluminum ($\sigma = \rho/\rho_0 = 2.57$) at a pressure $p = 10.85$ Mbar are presented.

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The primary sources of experimental information on the thermodynamic properties of a substance at high pressures are shock wave experiments (see, for example, Ref. 1). The shock compressibility of some substances used as standards is determined by the stopping method. Other materials are generally studied by the reflection method,

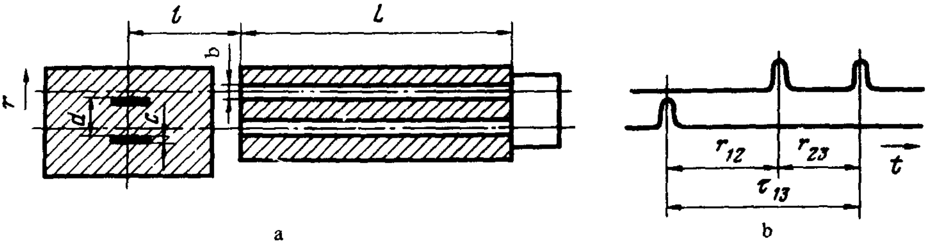

FIG. 1. Schematic of experimental apparatus for measuring D and u (a) and the recorded time intervals (b).

based on knowledge of the compressibility of a standard material. The upper value of pressures achieved in laboratory explosion studies of the dynamic compressibility in materials such as aluminum does not exceed 5–6 Mbar.[2] The results of calculations on the basis of the Thomas-Fermi model are used at pressures in excess of 100 Mbar, and various interpolation methods are employed in the intermediate region.

In recent years, experimental data for the relative compressibility of several metals, water, and quartzite[3–6] have been obtained. In particular, these data were used in Ref. 7 to check refinements of the statistical model of a dense material.

At the same time, a number of theoretical papers (see, for example, Refs. 8–13) indicate on the basis of more rigorous quantum-mechanical models that the electron shell structure of atoms leads to oscillations of the thermodynamic functions. The value of both the universally used "smooth" interpolations of the equations of state as well as the information on the relative compressibility is reduced in this case. To verify the new theoretical concepts and to gather reliable quantitative data, it is necessary to measure the shock compressibility by a direct method, for example, by a direct measurement of the shock wave velocity D and the mass velocity u of the material behind the front (or $D-u$). The laws of mass, momentum, and energy conservation make it possible to determine the thermodynamic parameters of the corresponding state of the material: the compressibility $\sigma=\rho/\rho_0=D/(D-u)$, the pressure $p=\rho_0 Du$ and the internal energy $\epsilon=p(\rho-\rho_0)/2\rho_0\rho$ (ρ and ρ_0 are the density of the material behind and in front of the wavefront).

The measurement of D, which causes no particular difficulty, is done by means of contact or optical sensors. The well-known methods[1] of measuring u are restricted to pressures below 1 Mbar. A new method has been suggested[14] for measuring the mass

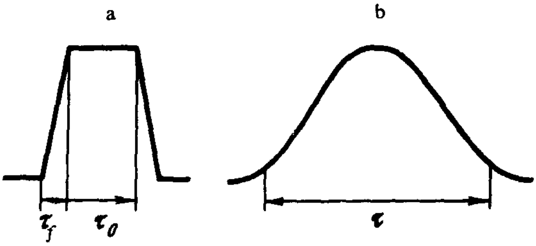

FIG. 2. Idealized (a) and real (b) shapes of γ-ray pulse.

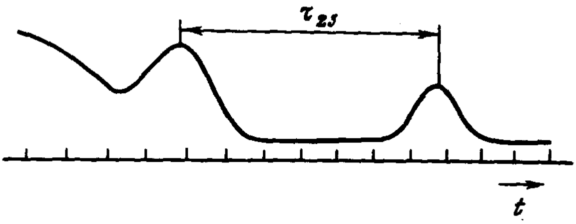

FIG. 3. A copy of the oscillogram. The notches represent 0.2 μsec.

velocity from the Doppler shift of the resonance absorption energy of neutrons with an energy of 0.3–1 keV by the nuclei of the moving material for the conditions of underground explosions. A velocity of $u = 10.7$ km/sec for $D = 18.2$ km/sec was recorded in molybdenum by using this method, i.e., shock compressibility data have been obtained at $p = 20$ Mbar.

In this paper we suggest another method for measuring the mass velocity, which is also applicable at high pressures. The quantities D and u are measured using flat specimens of the investigated material by recording the motion of the γ-reference points. The determination of D requires one reference layer and two slit collimators parallel to each other, whose distance between the planes is the measurement base a (Fig. 1a). We need another reference point to determine D. The reference layers and the collimators must be parallel to the surface of the investigated shock front.

During the passage of the reference points past the collimator slits the γ-ray detectors record three signals (Fig. 1b). Thus, $D = a/\tau_{12}$ and $D - u = a/\tau_{23}$. The establishment of additional reference points and collimators makes it possible to determine experimentally the damping of the shock wave due to the non-steady-state effect. The idealized signal has a trapezoidal shape with a rise time $\tau_f = lb/uL$ and a vertex $\tau_0 = b/u$ (Fig. 2a). The real signal from a reference of finite thickness has a smooth shape due to the scattered γ quanta for a duration $\tau \approx (2\,lb + Lb + Lc)/uL$ (Fig. 2b).

On the other hand, to reduce the gas-dynamic effect of the reference layer, its thickness must be as small as possible and its density must be close to that of the investigated materials; on the other hand, the amount of reference material must be sufficient to obtain a detectable γ flux. The corrections due to the gas-dynamic effect of the references and also due to a small deviation of the motion from the steady-state condition are taken into account in the analysis of the experimental data.

To ensure reliable detection of the signals, the γ activity of the references must amount to at least 10^7 Curie. This activity is determined by the design of the measurement apparatus, the sensitivity of the detectors, etc. Such a source cannot be stationary and must be produced immediately before arrival of the shock wave in the measurement apparatus. This is accomplished by introducing into the reference layer isotopes with an anomalously large radiation capture cross section (for example, europium). During the measurements the apparatus with the investigated material is irradiated with a high-intensity neutron flux.

The reliability of the measurements depends strongly on the background radiation. Therefore, this method should be used for materials with a small radiation

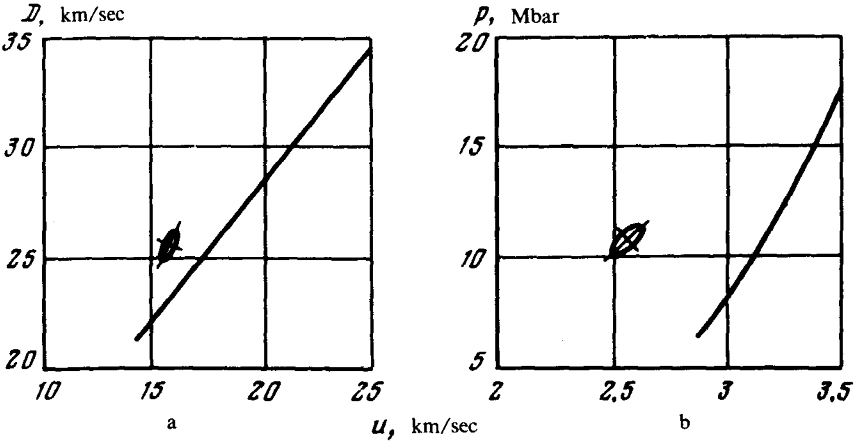

FIG. 4. Location of the experimental point in the D, u (a) and p, σ (b) planes.

capture cross section. In particular, experimental results for aluminum were obtained in 1975.

The measurement apparatus consisted of three, 50-mm-thick aluminum plates (AD-1, 99% aluminum, $\rho_0 = 2.71$ g/cm^3) between which two 100-mm-diam, 5-mm-thick pellets pressed to a density of 2.7 g/cm^3 from europium oxide with an organic binder, were placed. The collimator, whose slits had dimensions of 4×110 mm^2, was mounted perpendicularly to the axis of this assembly. The γ radiation was recorded by means of type FEK-12 photocells with a thin scintillator layer. Like in Refs. 3 and 14, the gas-dynamic motion was produced by a strong explosion. Figure 3 is a typical oscillogram which shows the signals that carry the information and background. The D and u values, which were measured on a base of 50 ± 0.14 mm, are 25.77 and 15.26 km/sec, respectively, and 25.65 and 15.67 km/sec, after taking into account the effect of the pellets and the non-steady-state effect. In this case the compression at the front is $\sigma = 2.56$, the pressure is 10.85 Mbar, and the internal energy is 0.1228 MJ/g.

The error in measuring the values of D and $D - u$ with a confidence coefficient of 0.95 is $\Delta \ln D = 2.1\%$, $\Delta \ln(D - u) = 1.5\%$. In other variables this leads to an error ellipse of the form

$$(\cos\phi\,\Delta\ln y - \sin\phi\,\Delta\ln x)^2\,\alpha^{-2} + (\sin\phi\,\Delta\ln y - \cos\phi\,\Delta\ln x)^2\,\beta^{-2} = 1,$$

where ϕ is the angle between the x axis and the major axis of the ellipse, $x = D$ or u, and $y = u, p$, or ϵ. In the (D,u): $\phi \approx -30°$, $\alpha = 0.005$, $\beta = 0.041$; in the (σ,p) variables: $\phi = 23°$, $\alpha = 0.06$, $\beta = 0.01$; in the (σ,ϵ) variables: $\phi = -19°$, $\alpha = 0.075$, $\beta = 0.0085$.

The location of the experimental point (with an indication of the error ellipses) relative to the interpolation shock adiabat from Ref. 7, which takes complete account of the previous experimental information and the data of the refined Thomas-Fermi model, is shown in Fig. 4 in the (D,u) and (p,σ) variables. The deviation exceeds the error of the measurements; this apparently indicates an oscillation of the shock adiabat due to the shell nature of the electronic structure.

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