Determination of the shock compressibility of iron at pressures up to 10 TPa (100 Mbar)

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(Submitted 1 February 1993)
Zh. Eksp. Teor. Fiz. **103**, 2189–2195 (June 1993)

Results are given of a determination of the shock compressibility of iron,[1)] using the deceleration method, by recording the speed of flight of an iron striker, set off with the help of the energy of an underground nuclear explosion, and the speed of the shock wave arising in the target when the plate struck it. In two experiments, similar in arrangement, the following parameters were obtained which characterize the state of the specimen studied: speed of flight of the plate $W = 60.8$ and 42.70 km/s, corresponding speeds of the shock wave $D = 43.5$ and 32.4 km/s and shock compression pressures 10.5 TPa and 5.43 TPa.

INTRODUCTION

The problem of determining the compression of matter at pressures considerably exceeding the range of laboratory experiments was solved in 1966 when Al'tshuler *et al.*[1] were the first to carry out measurements in underground nuclear explosions of the relative compressibility of an iron-lead system at pressures of 30 Mbar. In recent years our efforts[2-9] and those of American scientists[10-13] have substantially broadened both the class of materials studied under such conditions and the limit of realizable pressures.

However, the measurements were mainly of a comparative nature and those few numerical results published of the results of determining the absolute compressibility were either not completely successful in their accuracy[12] or were characterized by relatively small increases in the pressure range compared with laboratory data.[8]

The problem of determining the compressibility of metals by absolute methods thus is still of experimental interest. It was solved to a considerable extent by Trunin *et al.*,[14] in which the compressibility of lead was obtained at pressures of 4.2 TPa. In a footnote Trunin *et al.*[14] also gave the parameters of still another experimental point (at $P \simeq 5.4$ TPa) without any comment, which was obtained at the same time that Ref. 14 was already in press.

It is of course, desirable to give an explanation of that result. Furthermore, we also want to increase the range of pressures studied, all the more since we had such an opportunity—we had rough results of one of the 1970 experiments with a powerful explosion, in which conditions were realized for producing about a hundred megabars pressure in iron, This measurement range is also essential for interpretating results on determining the relative compressibility of materials for which iron had been used as a reference metal.

Interpretation of the results required a careful analysis of the operation of the sensors, the taking into account of the asymmetry in flight of the striker and the shock wave in the target, attenuation of the electrical signals on transmission through long cable lengths, etc.

It appeared possible to determine the iron compression parameters at recorded pressures of 5 and 10 TPa with acceptable accuracy as a result of such an analysis.

APPARATUS AND EXPERIMENTAL RESULTS

The layout of the experimental apparatus is shown in Fig. 1. In conjunction with it at a chosen distance from the explosive source of energy release a polished plane platform was arranged in the rock and was perpendicular to the direction of motion of the shock wave front. The diameter of the platform was $\simeq 1.5$ m. Parallel to its plane at a distance from it of 400 mm was situated the acceleration block of the striker, consisting of a 250 mm thick light polystyrene foam striker ($\rho_{00} = 0.03$ g/cm^3) and a 25 mm thick steel striker plate. The acceleration path of the plate, until its collision with the receiving steel target was 350 mm.

The construction of the apparatus differs from that described earlier[14] in the absence of a layer of air between the screen and the polystyrene foam striker. As calculations showed, from the point of view of the optimum loading conditions, both the system described earlier[14] and that discussed here are identical.

By optimum conditions, we mean, first, achieving a minimal difference between the flight velocity W of the striker and the doubled mass velocity $U(\bar{D})$ in the target, and secondly, achieving at least in the last part of the experimental recording a smooth pick-up of the striker and the constancy of its velocity.

As a criterion for calculating the closeness of the chosen system to the optimal we use the parameter $\alpha = U(\bar{D})/W$. Here $\bar{D}$ is the mean velocity of the shock wave in the target, and $U(\bar{D})$ is the mass velocity corresponding to $\bar{D}$ when using the equation of state of iron in the calculations. W is the calculated velocity of the striker flying to the target. Under ideal conditions the optimal values are $\alpha = 0.5$ and $U(\bar{D}) = W/2$.

In choosing the measuring system, detailed calculations were carried out of the processes taking place at the explosion which took account of the stage in which the energy of the explosion was liberated and propagated, the formation of a strong shock wave at the walls of the cavity where the explosive device is positioned, the propagation of

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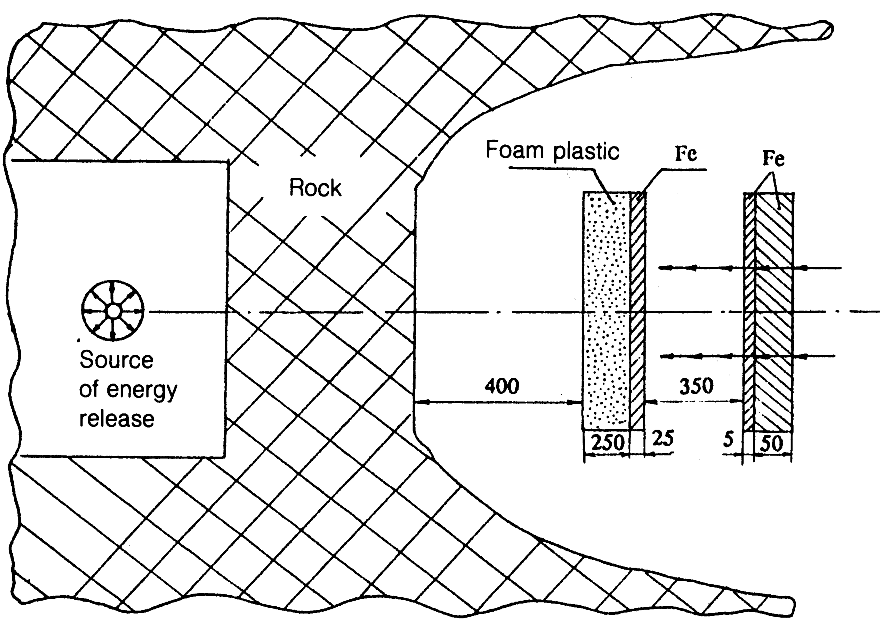

FIG. 1. Scheme for carrying out the measurements.

the wave through the rock, its emergence at the measuring platform, the scattering of the rock, the formation of a wave in the plastic, the transfer of energy to the steel striker, the acceleration of the plate and its impact on the target.

Equations of state of the Mie–Grüneisen type (with constant values of the parameters) were used in the gas dynamic stage of the motion of the shock waves; the ideal gas equation of state was used for the plastic with $\gamma = 2/3$.

We will give here some calculated parameters for the

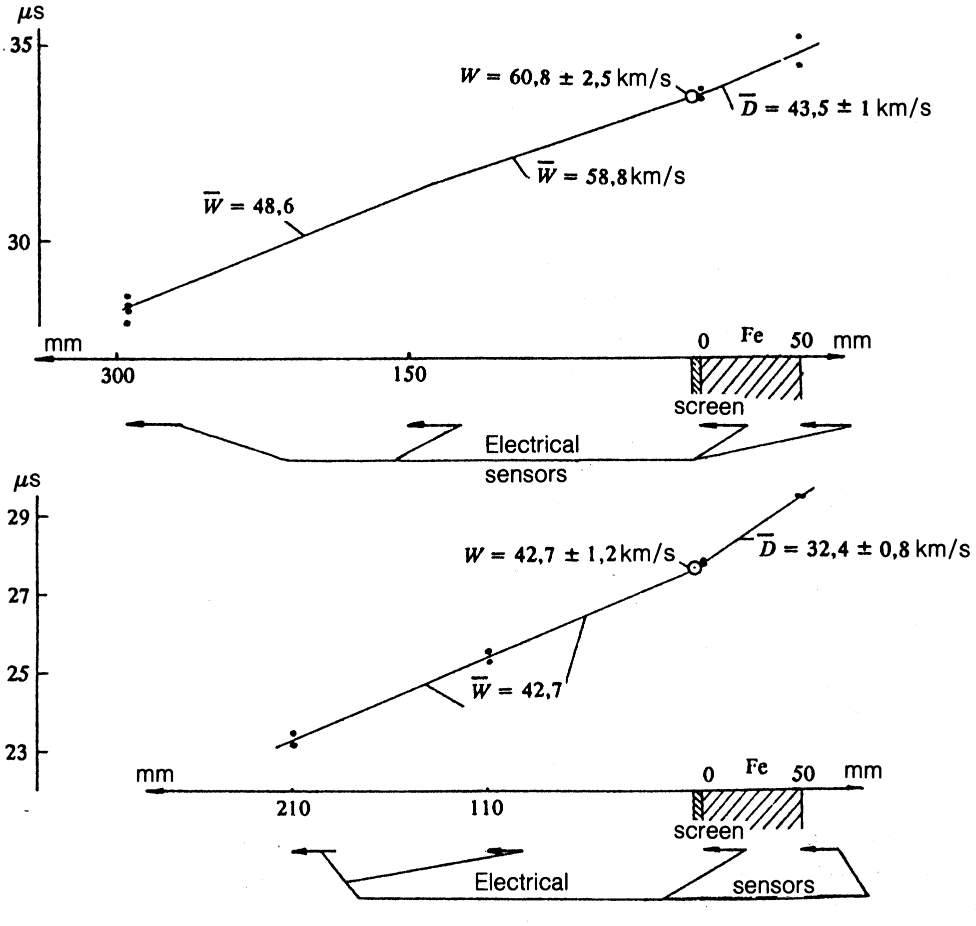

FIG. 2. Experimental $x - t$ diagram. W—average velocity.

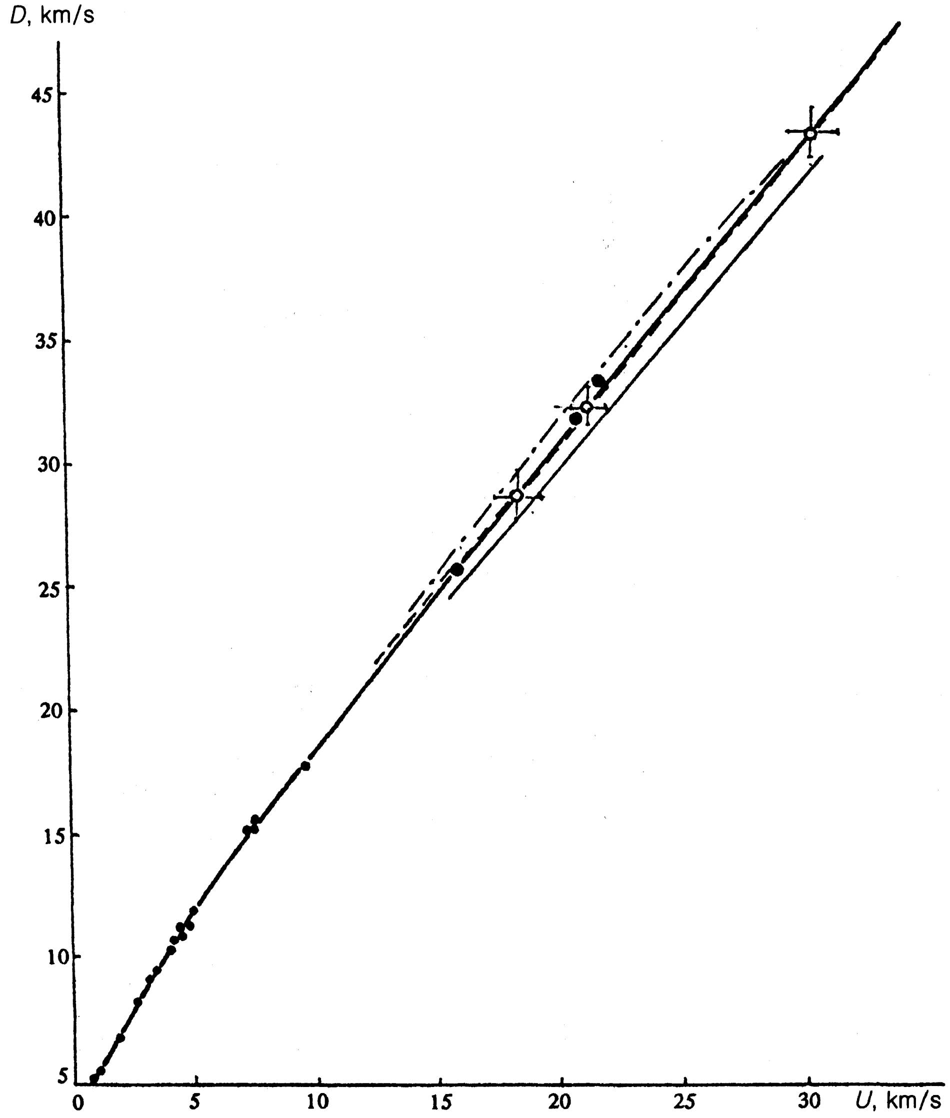

FIG. 3. Shock adiabat of iron. •) laboratory determinations, ●) comparative determinations under proving ground conditions ⌖) absolute measurements under proving ground conditions —) experimental adiabat ---) TFQ model[20,21] -·-·-) SCF model[23] —) HFS model[22].

system, in which the explosive energy was a maximum: the pressure of the shock wave in the ground before emerging onto the measuring area was of the order of 25 Mbar, the pressure of the first wave in the Fe striker was $\simeq 4$ Mbar (in the absence of the plastic striker the pressure in the plate was $\simeq 13$ Mbar).

Before the impact the plate has a roughly constant velocity not very different from the experimental speed. The optimization parameter was $\alpha \simeq 0.503$, i.e., the system is quite satisfactorily optimized.

In the second system (for smaller shock wave intensities) the calculated parameters (W, D) were still closer to their optimal values, so that the difference between W and $2U$ in this system could in general be disregarded.

It is natural that the calculated parameters of the system introduce some error into the final results. However, the experimental errors certainly exceed those which arise because of errors in estimating α.

The velocities were measured experimentally with a system of electric-contact sensors,[14] which were positioned at several levels along the flight path of the plate. A separate group of contacts was used for recording $\bar{D}$; 2–4 sensors were placed at each level. Experimental plots of transit time on the final acceleration path for both systems described are shown in Fig. 2.

The difference between the actual measurements (on separate channel-circuits) and the averaged dependences are more noticeable in a system with the maximum parameters, as would be expected.

The results obtained and the corresponding errors in determining the mean values are given below

System 1: $W=60.8\pm 2.5$ km/s,
$U=30.6$ km/s,
$D=43.5\pm 1$ km/s,
$P=105$ Mbar,
$\sigma=3.37$.

System 2: $W=42.70\pm 1.2$ km/s,
$U=21.35$ km/s,
$D=32.40\pm 0.8$ km/s,
$P=54.3$ Mbar,
$\sigma=2.93$.

The experimental points are compared with the results of absolute measurements of the compressibility of iron in laboratory[15-19] and field[14] conditions, and also with results of comparative measurements[1,3,11] in Fig. 3.

Figure 2 illustrates the continuous transition of an adiabat from the laboratory region of determinations to the high pressure region. For $D \simeq 13$ km/s a change in the slope dD/dU takes place from 1.59 to 1.24. The latter value, as is known, is characteristic for the ultrahigh pressure region, determined from theoretical models.[20] Good agreement is seen between the results of absolute and relative measurements in the range of maximal parameters for the experiment. We note in this connection that the relative results[1,3] were obtained in Pb–Fe measuring systems, where lead was used as the reference metal, for which the shock adiabat corresponded to interpolation between the region of laboratory determinations and the TFQ calculated dependence.[20,21] The agreement between the absolute and comparative results confirms the validity of the interpolation chosen for the lead reference, and consequently the justified applicability of the TFQ model for such calculations.

Within the limits of absolute measurements the results obtained at high pressures can be represented by a linear dependence of wave velocity on the mass velocity:

$D = 6.41 + 1.213U$, $\rho_0 = 7.85$ g/cm^3, D and U in km/s, valid within the range of wave velocities 25 km/s $< D < 50$ km/s.

In view of the existing uncertainties in the experimental points there is no basis for using other than linear D–U relations.

Calculated results are also shown in Fig. 3 obtained from different theoretical models: the modified Thomas–Fermi (TFQ), Hartree–Fock–Slater (HFS)[22] and self-consistent field (SCF)[23] [1)] models. It can be seen that in the region of high-pressure experiments ($D > 25$ km/s) the calculated dependences does not differ greatly from the assumed description of the experimental results. At the same time the largest difference is observed for HFS; of the others the TFQ model best corresponds to experiment.

We note in conclusion that the results obtained solve the question of the interpretation of results on comparative compression, since the the wave velocities of the materials studied can be calibrated in terms of the adiabat of iron, allowing present (or future) comparative measurements to be "transferred" absolute ones by means of the reflection method.[24]

Thus the problem of absolute shock compressibility measurements up to pressures of 100 Mbar is solved.

[1)] More precisely an interpolation equation connecting calculations according to the SCF model with the laboratory experimental region.

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Translated by Robert Berman