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Explosive laboratory devices for the measurement of the dynamic compressibility of porous substances in the pressure range from 0.1 to 1 TPa

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Abstract. Earlier [1], a historical review of the Russian Federal Nuclear Centre (Sarov, Nizhniĭ Novgorod region) work on explosive laboratory devices for dynamic compressibility measurements was given, but most of the devices described were mainly applied to substances with the normal initial density. In the present work, another Sarov explosive devices of the late 50's are described with which the dynamic compressibility of porous metals and porous ionic compounds were determined [2 – 4].

The studies made at the Russian Nuclear Centre (Sarov) in the early 1960s on the shock compression of some porous metals and ionic compounds [2 – 4] used explosive-loading devices specifically designed for the purpose. They were not described in [2 – 4], and this made the information about the results less complete and precluded their verification and reproduction. At this writing, several measuring devices intended mainly for studies of the shock compression of substances with normal initial density can be found in [1], but they include only one explosive-loading device used in [2 – 4].

For their operation, explosive-loading devices that serve to generate strong shock waves in condensed media for measurement purposes depend on the acceleration of an impacter placed inside a hemispherical cavity of the charge of explosive. Inside the charge, a convergent detonation wave is generated by a system of suitable initiating charges arranged on its outer spherical surface. By virtue of the sphericity, as the detonation wave propagates toward the centre, the pressure at its front builds up significantly. In consequence of this feature, the impacter — a hemispherical iron (or low-carbon steel) shell — is accelerated to a velocity markedly higher than when an explosive charge propels a flat plate and generates a flat detonation wave. As it approaches the centre, the shell picks up speed owing to the action of the explosion products and the sphericity. The arrangement for the first device of this type was proposed by L V Al'tshuler, E I Zababakhin, Ya B Zel'dovich, and K K Krupnikov. The device was brought to operational status and the motion parameters of the shell were determined with the participation of V I Zhuchikhin, B N Ledenev, and M I Brazhnik.

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Even in the early studies concerned with the shock compression of some metals, this device, which came to be known as the 'Big Model' (BM), was able to build up pressures close to 0.5 TPa [5 – 7]. Initially, the shock compression adiabat for iron was determined in [5]. The shock compressibility of other metals was determined by the reflection technique [8]. With this technique, the state of the specimen was deduced from the velocity of the shock wave in it and from the state of the iron shield recorded previously on a shock adiabat.

The shock compression adiabat for iron was mainly measured using the 'backing' technique [5]. After the first results presented in [5, 8] were obtained, the parameters necessary to determine the shock compressibility of the materials under study were refined owing to the additional measurements made by A A Bakanova, M I Brazhnik, and A I Funtikov, and also in view of the corrections applied to allow, in particular, for the difference in convergence, i.e. the rate of acceleration toward the centre, between the shell in its free motion and the shock wave in the material.

In the case of porous materials which originally had a microinhomogeneous structure, it was thought advisable to measure the velocity of a shock wave in specimens with a gauge length of 6 to 10 mm as against a gauge length of 3 or 4 mm in structurally homogeneous specimens [8, 9]. Because of this, it was required that, just as it struck the shield, the impacter-shell should have a thickness sufficient to avoid, for the chosen gauge length, the effect of the overtaking decompression wave which propagated away from the outer boundary of the shell [10]. The BM device satisfied this requirement because the shell was 4.8 mm thick initially and its thickness increased more than threefold by the instant it struck the shield.

S B Kormer, A I Funtikov, and A I Kuryapin developed two more devices, designated KZ and DK. The devices extended the range of shock compressibility for porous materials toward both higher (up to 1 TPa) and lower (down to 0.1 or 0.2 TPa) pressures. The KZ device, similar to its BM counterpart, used a thicker and, hence, more slowly accelerated steel shell. The DK device was of a two-stage construction.

The principle of multistage acceleration was investigated by E I Zababakhin, and the first measuring explosive device using a hemispherical explosive charge was developed by L V Al'tshuler, K K Krupnikov, and M I Brazhnik [1]. For the first stage, the shell of a BM device was employed. The second stage made up a hemispherical layer of explosive charge which was to accelerate a steel shell 2 mm thick. As observed at a gauge radius $r_{\mathrm{obs}} = 0.068\, R_{\mathrm{ch}}$, the velocity of the shell was 15.7 km/s. With this two-stage measuring device,

Table 1.

Device	r_{sh}/R_{ch}	Δ, mm	r_{obs}/R_{ch}	W, km/s	Shield	P, GPa	U, km/s
KZ	0.523	11	0.21	4.85	Fe	0.146	2.41
BM	0.4	4.8	0.137	8.64	Fe	0.357	4.26
DK, 1st stage	0.45	2.8	—	—	—	—	—
DK, 2nd stage	0.227	3.15	0.08	15.45	Fe	0.924	7.67
	0.227	3.15	0.08	15.45	Al	0.493	9.95

pressures close to 1 TPa were obtained for the first time for iron [11], and, with the observation radius reduced to $r_{obs} = 0.045\ R_{ch}$, the shock compressibility for iron was taken at a pressure of 1.3 TPa [12].

The shock compression of porous specimens with a gauge length of 8 mm was observed at a radius $r_{obs} = 0.08\ R_{ch}$. In view of the requirements stated above, the shell thickness was increased by a factor of 1.5. The thickness of the shell in the first stage was reduced and its position inside the explosive charge cavity was optimized to maintain the high velocity of the shell at the observation radius. The second stage of explosive used an aluminium spacer to minimize its inhomogeneity and thus improve the symmetry of shell motion. The possibility of using an inert material to accelerate the shell in a multistage device was substantiated by E I Zababakhin [13]. Unfortunately, because of the aluminium spacer, the second-stage steel shell was raised to a higher temperature as it was accelerated.

An iron shield was used in [2] and [4], and an aluminium shield in [3] to measure the shock compression of continuous and porous substances by the reflection technique. The original state variables of the shield material at the observation radius were deduced from the velocity of the shock wave and also from the velocity of the striking shell allowing for its heat build-up in the course of acceleration.

The parameters of the devices used to measure the shock compressibility of porous materials are listed in the accompanying Table 1. The table also gives the relative radii R_{sh} and R_{obs} for the location of the shell and the observation point, respectively, the shell thickness Δ, the shell velocity W, the shield material, and the parameters of the shock wave in the shield (pressure P and mass velocity U).

With the two-stage explosive-loading device, record values of shock-compression parameters were obtained for aluminium and five ionic crystals in [3], and for porous aluminium, copper, nickel, lead, and tungsten in Refs [2, 4], in the pressure ranges of 0.1 to 0.5 and 0.4 to 1 TPa, respectively.

A special point about explosive-loading devices in which the shell experiences a spherically converging acceleration was the necessity of introducing corrections needed to be applied to the shock-wave parameters measured in various materials. This had to be done because the rate of acceleration of the shock wave in its motion toward the device centre was different over the distance from the shield – specimen interface to the midpoint on the gauge length in the shield and in the specimen. This difference, governed by the flow of the material behind the shock-wave front, could be deduced by numerical gas-dynamics calculations in one-dimensional spherical geometry, where simplified Mie – Grüneisen equations of state of substances with constant Grüneisen coefficients corresponding to the compression limit were used to a first approximation.

Another correction had to be applied to allow for the difference between the local shock-wave velocity as measured at the observation radius and the average velocity as measured over the gauge length. The corrections increased in value with a decrease in the observation radius. In fact, the two corrections referenced the states at the shock-wave front in the shield and the specimen to the observation radius. For the specimens investigated in Refs [2, 4], which exhibited densities close to that of the shield material, these corrections as referred together to the measured shock-wave velocity were small, being 0.2, 0.4, and 1.2% for the KZ, BM, and DK devices, respectively. For specimens with a density of about 3 g cm^{-3}, they increased to 1% for the KZ and BM devices, and to 3% for the DK device.

Lastly, there was a third correction. It was applied to the results measured by the reflection technique to allow for the difference in the behaviour of pressure with mass velocity between the single-stage compression shock adiabat taken in a first approximation by the 'specular reflection' technique [14] and the expansion isentrope or the double-stage compression adiabat of the shield reference material. This correction increased in value with an increase in the difference in the pressure and mass velocity of shock waves between the shield and the specimen.

The advent, in the late 1950s, of laboratory explosive-loading devices using hemispherical explosive charges laid the foundation for a new line of attack in the dynamical studies of extremal states of substances, which has matured largely owing to Ya B Zel'dovich, L V Al'tshuler, and S B Kormer.

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