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POROUS-SPECIMEN ADIABATS AND SOLID-COPPER EXPANSION ISENTROPES

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Experiments on shock compression of porous bodies are important in providing information on the thermodynamic parameters of substances at high pressures and temperatures. Specimens of low initial density enable one to obtain higher energies and temperatures with a given specific volume for the shock-compressed material.

It is usually assumed in interpreting experiments with porous specimens that at pressures above the collapse one, at which the density is close to that of the continuous material, the temperature has time to equalize during compression at the shock-wave front, i.e., the states attained are equilibrium ones. However, this requires experimental test.

In [1], the grain size was varied from 0.5 to 100 μm, but no effect on the shock-wave speed was found. This indicates thermal equilibrium for compressed porous specimens.

Here we propose another way of checking the state equilibrium in shock-compressed porous specimens. The thermodynamic parameters of the compressed material are checked from the state parameters derived on unloading a previously compressed solid material. The monitored parameter was the density, and the values were compared for identical pressures and internal energies realized in two different processes. The density comparison for copper shows that the effects of possible deviations from equilibrium during compression of porous specimens do not exceed 1.5% at pressures above 20 GPa.

1. The state of the material in a single-phase system is completely defined by any two thermodynamic parameters if the process is a thermodynamically equilibrium one. If one chooses for example the pressure p and energy E as these, the one can compare the densities ρ or specific volumes v = 1/ρ on porous shock adiabats and expansion isentropes for the solid material for identical p and E to check the consistency in the data and thus to observe possible deviations from thermal equilibrium.

A schematic p—u diagram is used (Fig. 1) to explain the method. In the initial state, the expansion isentrope 2 for a solid specimen on the shock adiabat 1 is characterized by the parameters p_a, u_a, $E_a = u_a^2/2$ ($E = 0$, $p = 0$, $T = T_0$); as the shock-compressed specimen expands, the internal energy decreases. The transition from the hydrodynamic p—u variables to the thermodynamic p—ρ—E ones on the expansion isentrope 2 is provided by calculating the Riemann integrals that express the conservation laws for this type of self-modeling flow:

$$\rho_s(p) = \left[v_a + \int_{u_s}^{u_a} \frac{du}{(dp/du)_s}\right]^{-1}, \quad E_s(p) = E_a - \int_{u_s}^{u_a} p\,\frac{du}{(dp/du)_s}, \tag{1.1}$$

where the subscripts a and s relate correspondingly to the state on the shock adiabat and on the expansion isentrope. The $E_s(p)$ relation along the isentrope for the solid material can be converted to the p—u relationship 3, on which $u(p) = \sqrt{2E_s(p)}$. In the same coordinates,

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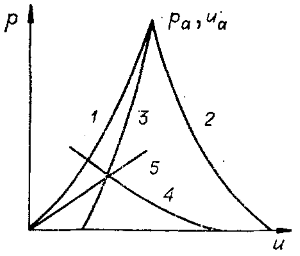

Fig. 1

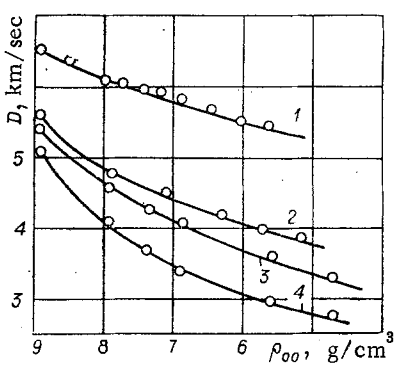

Fig. 2

the stopping line 4 is known for the screen material in the impact device used in measuring the shock-wave speeds in the porous specimens. The point of intersection defines p and u for the porous material, and from the ratio of them one gets the slope of the wave ray 5: $p = \rho_{00}D(\rho_{00})u$. Also, the pressures and internal energies of the solid and porous materials are equal at this point. Further, one uses the observed $D(\rho_{00})$ relationship, which can also be represented as $\rho_{00}D = f(\rho_{00})$, to determine the initial density ρ_{00} and the wave speed D. The law of conservation of matter at the shock-wave front gives us the density $\rho_g = \rho_{00}D/(D - u)$, which may be compared with the density ρ_s on the isentrope defined from (1.1), which is known for pressure p.

2. This method of comparing the specific volumes at given pressures and internal energies has been implemented in experiments with copper. We determined the dependence of the wave speeds on the initial density with four leading devices and derived three expansion isentropes for solid copper.

The porous copper specimens were prepared from PM-2 powder with a particle size less than 50 μm by hydrostatic pressing of disks of diameter 12 mm and height about 3 mm. We measured the shock-wave speeds in specimens of various initial densities by an electrical contact method in four series of experiments. Each series employed the same Al screen material and the same shock-wave intensity in it.

Table 1 gives the results on the wave speeds and shock-wave parameters in the aluminum screens. The wave speeds are averages from four to eight experiments. The $D(\rho_{00})$ curves (single-charge lines [1]) are shown in Fig. 2 for explosive devices differing in intensity. Each point on a single-charge line defines the shock-compression parameters for a specimen of closely defined initial density on the basis of the condition for equality of p and u at the specimen–screen boundary and the equation describing the change in state of the screen material in p–u coordinates. This makes it possible to construct shock adiabats for any porosity and to compare the data obtained by different workers.

For this purpose, the data of Table 1 were used to determine the parameters of the points corresponding to shock adiabats for specimens with densities ρ_{00} = 7.90, 7.35, 6.35, 5.72 g/cm^3, and the comparison was made with the data of [2], in which direct experiments were performed on the dynamic compressibilities of copper specimens with these densities. In deriving the shock-compression parameters, the screen loading lines were identified in the p–u plane with the mirror reflections of the shock adiabat for aluminum [3] with respect to vertical straight lines passing through the initial states of the screens. Figure 3

TABLE 1

p=65,8, u=2,70				p=36,3, u=1,74		p=30,5, u=1,52		p=21,7, u=1,16	
ρ_{00}	D	ρ_{00}	D	ρ_{00}	D	ρ	D	ρ_{00}	D
8,93	6,53	7,25	5,92	8,93	5,58	8,93	5,40	8,93	5,08
8,52	6,38	6,89	5,79	7,90	4,70	7,92	4,55	7,92	4,05
8,00	6,10	6,50	5,66	7,11	4,44	7,38	4,22	7,38	3,67
7,75	6,02	6,05	5,50	6,33	4,16	6,86	4,02	6,86	3,41
7,48	5,94	5,64	5,44	5,69	3,96	5,57	3,63	5,57	2,92
				5,18	3,85	4,67	3,29	4,67	2,74

p, GPa; u, km/sec; ρ_{00}, g/cm^3; D, km/sec.

TABLE 2

Obstacle material	Isentrope 1			Isentrope 2			Isentrope 3		
	D, km/sec	u, km/sec	p,GPa	D, km/sec	u, km/sec	p, GPa	D, km/sec	u, km/sec	p,GPa
Copper	8,32	2,95	219,2	7,49	2,39	159,9	6,53	1,75	102
Iron	8,77	3,03	208,6	7,84	2,43	149,6	6,88	1,84	99,4
Aluminum	10,71	3,97	115,2	9,72	3,24	85,2	8,57	2,39	55,5
Magnesium	10,15	4,53	80,0	8,95	3,59	55,9	7,75	2,63	35,5
Teflon	9,22	4,45	89,4	8,07	3,73	65,6	6,40	2,67	37,3
Plexiglas	9,79	5,07	58,6	8,26	3,91	38,1	6,99	2,95	24,3
Polyethylene	10,00	4,83	44,4	8,86	4,07	33,2	7,33	3,04	20,5
Foam plastic $\rho_{0_3} = 0{,}70\ \mathrm{g/cm^3}$	8,29	5,26	30,5	7,01	4,31	21,1	—	—	—
Foam plastic $\rho_{0_3} = 0{,}30\ \mathrm{g/cm^3}$	7,54	5,73	13,0	6,25	4,73	8,9	—	—	—
Air	—	6,21	0,051	—	5,02	0,04	—	3,58	0,018

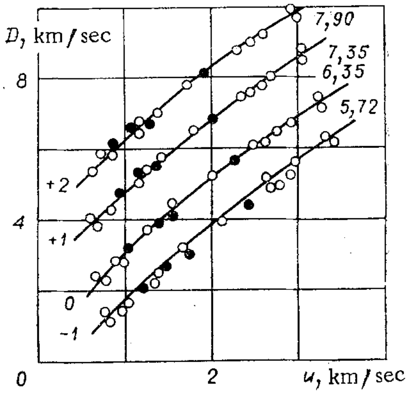

Fig. 3

TABLE 3

Isentrope	a_0, GPa	a_1,GPa/km/sec	a_2,GPa/km^2/sec^2
1	657,066	—187,651	13,18
2	472,789	—165,770	14,253
3	309,490	—147,767	17,169

shows that these D—u plots indicate good agreement between the results and the data of [2], which are denoted here by open symbols. The numbers to the left of the curves denote the displacement of each curve in D, while those on the right indicate the initial densities.

The obstacle method [4] was used to determine the expansion isentropes for previously compressed solid specimens. Less rigid materials with known dynamic adiabats were placed on the copper specimen. The shock compression of the solid specimens was provided with three measurement charges. The initial parameters of the compressed states for the first and second isentropes were realized with devices in which the strikers were steel plates of thicknesses 1.5 and 2.2 mm accelerated by the detonation products from explosives to speeds of 6.10 and 4.96 km/sec correspondingly. The third isentrope was obtained with a device having an aluminum striker of thickness 4 mm, whose speed was 5.40 km/sec. The same device was used in series 1 of experiments on the shock compression of porous specimens.

Electrical contact methods were used to record the wave speeds in the condensed obstacles and the dispersal speeds of the copper specimens in air. Many researchers have examined the shock adiabat for copper, and this was used with the known speeds of the strikers with p—u construction to calculate the initial states for the expansion isentropes. In each experiment, a copper disk was placed on the specimen together with the disks of obstacle materials, and the wave velocity in this was measured independently to check the initial state.

The results from the isentropic expansion of solid copper are given in Table 2, where each point has been obtained by averaging 6-10 experiments* for isentropes 1 and 2 or 12-20 experiments for isentrope 3. We used D—u relations published for metals in [3] and for the other substances in [4] to convert to the pressures and mass velocities in the obstacles.

The points in p—u coordinates were described by polynomials of second degree $p(u) = \sum_{i=0}^{2} a_i u^i$ with the coefficients given in Table 3.

The method given in Sec. 1 was used then to determine the state parameters of the copper at given pressures and energies corresponding to isentropic expansion of solid specimens and

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*The number of measurements was larger with copper specimens.

TABLE 4

States on isentropes				States on porous-specimen shock adiabats				
isen-trope	p_s, GPa	E_s, kJ/g	ρ_s, g/cm^2	$u=\sqrt{2E_s}$, km/sec	D, km/sec	ρ_{00}, g/cm^3	ρ_g, g/cm^3	$\frac{\Delta\rho}{\rho_s}$, %
1	89,7	2,091	11,36	2,045	5,91	7,42	11,35	0,1
	40,2	1,28	9,92	1,60	4,10	6,13	10,05	—1,3
	30,7	1,148	9,55	1,515	3,62	5,60	9,63	—0,8
	16,5	0,966	8,865	1,39	2,685	4,42	9,17	—3,4
	0,051	0,840	7,69					
2	96,0	1,796	11,81	1,895	6,19	8,18	11,79	0,2
	45,3	1,015	10,42	1,425	4,43	7,17	10,57	—1,4
	35,7	0,878	10,06	1,325	3,985	6,76	10,13	—0,7
	21,0	0,702	9,42	1,185	3,00	5,90	9,76	—3,6
	0,04	0,513	7,89					
3	49,3	0,825	10,91	1,285	4,80	7,99	10,91	0
	39,5	0,708	10,57	1,19	4,355	7,62	10,48	0,85
	24,8	0,535	10,03	1,035	3,44	6,97	9,97	0,6
	0,018	0,340	8,37					

shock-compression of porous ones. Table 4 gives the parameter values. Here also we give the densities for the isentrope realized in states corresponding to unloading copper specimens in air. The large column gives the relative difference between ρ_s and ρ_g. Table 4 shows that apart from two cases the relative differences in the densities do not exceed 1.5%, which indicates that the contribution from disequilibrium, if it exists, is very small on compressing porous copper at $p > 20$ GPa and that the requirements for thermal equilibrium can be neglected.

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