SHOCK COMPRESSIBILITY OF POROUS TUNGSTEN, MOLYBDENUM, COPPER, AND ALUMINUM IN THE LOW PRESSURE DOMAIN

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Results are presented of an experimental study of the behavior of four porous metals, tungsten, molybdenum, copper, and aluminum with an initial density corresponding to ≈30 and 50% of the density of the continuous (solid) material under loading by shocks with intensity between 10-800 kbar. The behavior of the shock compression curves in the $p-\rho$ plane shows that for some pressure p^* the compression of the porous substance to the state of a continuous material is completed. At initial densities ≈50% of the continuous substance, the values are $p^* = 65$, 40 and 35 kbar, respectively, for W, Mo, and Cu. At lesser densities (≈30% of the density of the continuous substance), the values of p^* are approximately halved as compared with those mentioned. The state of complete packing of the porous material into a monolithic solid was not determined in aluminum in the pressure range examined 6.5-200 kbar.

1. The behavior of porous substances, particularly metals, under shock loading from several to hundreds of kilobars, hasbeen studied in [1-6].

In contrast to the Hugoniot adiabat of continuous metals, the shock adiabats of porous metals in this pressure domain have singularities associated with the mechanism of their compression on the pressure–density ($p-\rho$) diagrams. These singularities cannot be described within the framework of the models for the equation of state developed in [7-9] for states with high pressures in which it was considered that the pressures p^*, the associate of a porous substance to a monolith, are ultimately small, and its shock adiabat was constructed from the initial state of the continuous substance. It is impossible to consider the construction of a model of porous material compression in the low pressure range perfected. Published results of investigations of their compressibility concern materials with comparatively low porosity and are partially contradictory [1, 2, 4, 6].

The specimens of the materials to be investigated were fabricated from powder with a particle size less than 100 μ by two methods. The specimens with almost bulk densities were prepared by packing thin-walled (0.1 and 0.2 mm thick) aluminum or copper boxes, and the specimens with greater density were fabricated by hydrostatic compression of pellets of 14-mm diameter. The specimen heights were 2-3.5 mm. The characteristics of the powders used in the experiments are presented in Table 1.

Explosive apparatus described in [10, 11] were used to produce shock pressures of different intensities in the materials being studied. The parameters of the explosive systems on which the investigations were performed are presented in Table 2.

The specimens were shock loaded through aluminum and copper screens.

The time of shockwave propagation in the speciment (D) was measured in the tests by an electrical contact method. The wave velocities were determined simultaneously for three distinct specimens in each of the tests whose diagram is presented in Figs. 1a and b. In Figs. 1a and b 1 represents the screen and

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TABLE 1

Material	Powder brand	Content of main material	Bulk porosity
Al_I	PAK-3	96	5.5
Al_{II}	AV-0	98.4	2.1
Cu	PM-2	99.7	4
Mo	—	99.7	3
W	PV	99.8	4.3

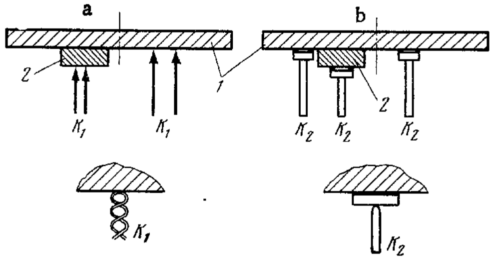

Fig. 1

TABLE 2

Number of measuring unit	Screen material	ρ_0 g/cm^3	Shock parameters in the standard		
			u_1, km/sec	D_1, km/sec	p_1, kbar
1	Copper	8.93	0.17	4.20	64
2	Copper	8.93	0.34	4.46	136
3	Aluminum	2.71	0.69	6.21	116
4	Aluminum	2.71	1.14	6.83	211
5	Aluminum	2.71	1.51	7.35	301
6	Aluminum	2.71	1.74	7.67	362
7	Copper	8.93	1.76	6.59	1031
8	Aluminum	2.71	2.76	9.09	680

2 the specimen; K_1 and K_2 are the "closed" and "open" contacts. The shockwave is incident on the screen from the top. In the low pressure range (shockwave amplitudes in the specimens are less than 100 kbar), open contacts K_2 (Fig. 1b diagram) were used in the form of thin metal rods separated by a fixed 0.03 mm gap from the screens and specimens. At the higher pressures, closed contacts (Fig. 1a) fabricated from insulated copper wire with 0.01-mm-thick insulation, which were delivered right down to the surface of the specimens and screens, were used in the specimens. The mean error in determining the wave velocities was 0.5-1%.

Data about the propagation velocities of the forerunners for Cu and W in [1, 2] were taken into account in determining the limits of application of any kind of transducers, and the limit was established for Mo and Al by conducting comparative experiments with different transducers on the same measuring unit. The experiments showed that the use of closed contacts in the low shockwave amplitude range yields a systematic exaggeration in D by $\approx 10\%$, which is apparently associated with actuation of the contacts due to the pressure in the forerunner.

The location of the shock adiabats of the metals investigated was determined by the method of reflection [12, 13]. The Hugoniot adiabats and the equations of state of the screen materials were taken from [10, 14]. The adiabats are described in the wave velocity (D)-mass flow rate (u) coordinates by the relationships $D=5.25+1.39\,u$ and $D=3.95+1.50\,u$ for Al and Cu, respectively.

The test data for the determination of the wave velocities D in the porous specimens and the shock compression thermodynamic parameters calculated thereby by using the conservation laws are presented in Table 3. Presented here are the initial densities of the porous (ρ_{00}) and solid (ρ_0) metals, the porosity $m=\rho_0/\rho_{00}$, the wave velocity D and their corresponding mass flow rates u, dynamic compression pressure p, quantities characterizing the relative compression of the porous material $m\sigma = D/(D-u)$ and the density $\rho = \rho_{00} m\sigma$. The number of the explosive apparatus is indicated in the first column.

2. The results of the experiments performed are represented graphically in the D–u diagram in Fig. 2 [1) Mo, 2) W, 3) Cu, 4) Al)] and in $p-\rho$ -coordinates in Fig. 3 for Cu (a) and Mo (b, upper scale), and in Fig. 4 for W. The points 5 in Figs. 2-4 correspond to the experimental data of Table 3 with the porosity $m \approx 2$, and the points 6 to $m \approx 3$. The shock adiabats of porous metals, constructed according to the D–u dependences, are shown in Figs. 3 and 4 by solid lines 1 for $m \approx 3$, 2) for $m \approx 2$ with initial states at the points 7 and 8 respectively for the porosities ≈ 2 and 3. The shock compression curves 3 of the solid material ($m=1$) are also shown in the $p-\rho$ diagrams according to the data in [8, 10, 13-15]. The arrows show the limits of the probable experimental spread of the series of test points.

It follows from Figs. 3 and 4 that the shock compression curves of porous W, Mo, and Cu have a characteristic form. In the low amplitude range (below p*) the density grows rapidly with pressure and

TABLE 3

Number of the measuring unit	Tungsten $\rho_0 = 19.17$ g/cm^3									
	$\rho_{00} = 10.59$ g/cm^3, m = 1.81					$\rho_{00} = 5.40$ g/cm^3, m = 3.55				
	D, km/cm	u, km/sec	p, kbar	$m\sigma$	ρ g/cm^3	D, km/cm	u, km/sec	p, kbar	$m\sigma$	ρ g/cm^3
1	0.87	0.27	24.9	1.451	15.38	0.62	0.31	10.4	2.000	10.80
2	1.16	0.52	63.8	1.813	19.20	0.85	0.61	28.0	3.542	19.13
3	1.56	0.70	116	1.814	19.21	1.31	0.95	67.2	3.640	19.71
4	2.21	1.03	241	1.873	19.84	2.03	1.41	154	3.270	17.60
5	2.67	1.29	365	1.935	20.50	2.50	1.77	239	3.425	18.50
6	2.93	1.44	447	1.966	20.82	2.78	1.98	297	3.475	18.76
7	4.04	1.98	847	1.961	20.77	3.60	2.51	488	3.303	17.83
8	—	—	—	—	—	4.19	2.86	647	3.150	17.01
	Molybdenum $\rho_0 = 10.20$ g/cm^3									
	$\rho_{00} = 5.59$ g/cm^3, $m = 1.82$					$\rho_{00} = 3.29$ g/cm^3, $m = 3.1$				
1	0.86	0.30	14.4	1.536	8.58	0.65	0.32	6.84	1.970	6.48
2	1.21	0.58	39.2	1.921	10.74	0.95	0.64	20.0	3.064	10.10
3	1.80	0.86	86.5	1.915	10.70	1.56	1.04	53.4	3.000	9.87
4	2.67	1.26	188	1.894	10.59	2.39	1.56	123	2.880	9.47
5	3.25	1.57	285	1.935	10.82	2.96	1.97	192	2.990	9.84
6	3.59	1.76	353	1.962	10.97	3.26	2.23	239	3.165	10.41
7	4.75	2.31	613	1.947	10.88	4.14	2.71	369	2.900	9.54
8	—	—	—	—	—	5.01	3.21	529	2.783	9.16
	Molybdenum $\rho_0 = 8.93$ g/cm^3									
	$\rho_{00} = 4.67$ g/cm^3, $m = 1.91$					$\rho_{00} = 3.00$ g/cm^3, $m = 2.98$				
1	0.84	0.30	11.8	1.556	7.27	—	—	—	—	—
2	1.31	0.60	36.7	1.845	8.60	0.98	0.64	18.8	2.882	8.65
3	1.91	0.89	79.4	1.873	8.75	1.68	1.04	52.4	2.625	7.87
4	2.74	1.33	170	1.943	9.07	2.45	1.59	117	2.849	8.55
5	3.29	1.69	2.60	2.056	9.60	3.19	1.98	189	2.636	7.91
6	4.66	2.44	531	2.100	9.80	4.36	2.73	357	2.675	8.02
	Aluminum $\rho_0 = 2.71$ g/cm^3									
	$\rho_{00} = 1.35$ g/cm^3, $m = 2.01$					$\rho_{00} = 0.9$ g/cm^3 $m = 3.01$				
2	1.41	0.65	12.4	1.855	2.50	1.09	0.67	6.60	2.595	2.33
3	2.60	1.12	39.3	1.757	2.37	2.09	1.23	23.1	2.430	2.19
4	3.60	1.76	85.5	1.957	2.64	3.11	1.93	54.0	2.636	2.37
5	4.36	2.25	132	2.066	2.79	3.92	2.49	88.0	2.741	2.47
7	5.71	2.97	229	2.084	2.81	4.94	3.16	140	2.775	2.50

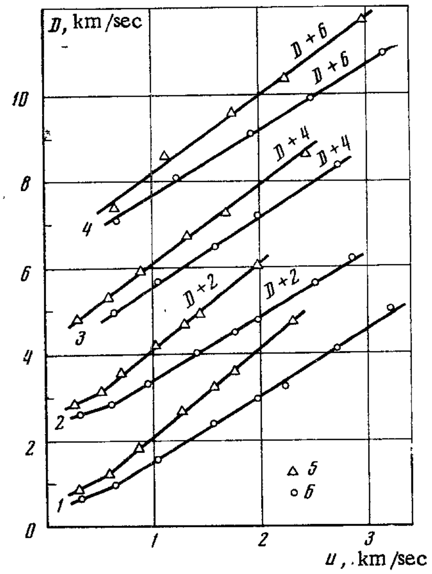

Fig. 2

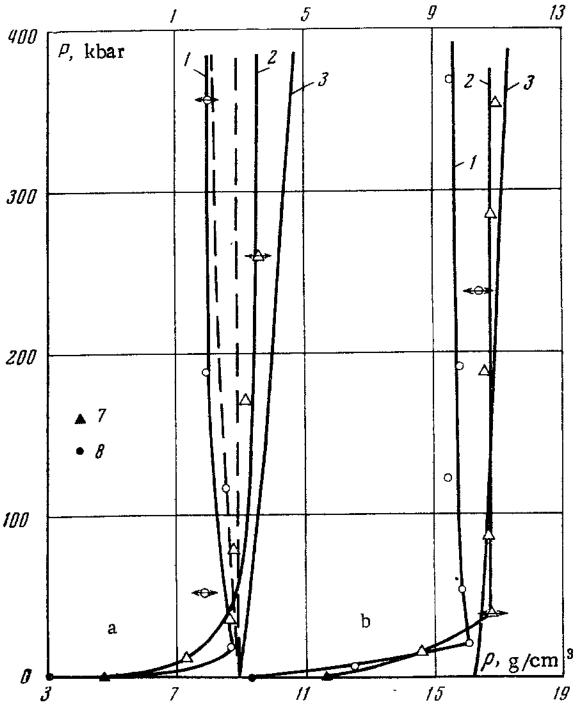

Fig. 3

becomes equal or close to the density of a solid material compressed to the same pressure p*, at the pressure p*. At pressures greater than p* these curves stand off from the compression curve for a solid material in the low density range, and even more so the lower the initial density of the porous material. For an initial density corresponding to the ≈50% density of a monolithic material, the total compression pressure is 65 kbar for W, 40 kbar for Mo, and 35 kbar for Cu. As the initial density is reduced, complete compaction is achieved at lower pressures. Thus, for a porosity of ≈30% of the solid material density, the values of p* are reduced to 30, 20, and 18 kbar for W, Mo, and Cu, respectively.

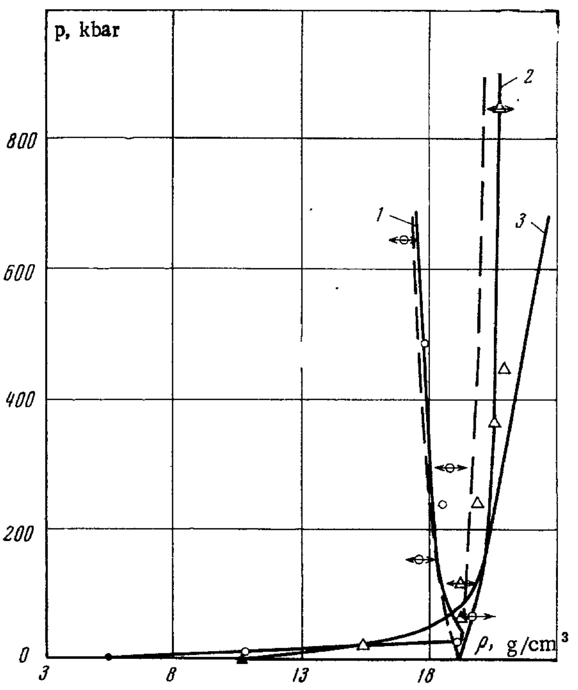

Fig. 4

The experimental points referring to pressures above p* in the domain investigated on the D-u diagrams were located along straight lines and can be approximated by relationships of the form $D = C_0 + \lambda u$ with almost zero values of C_0.

Physically, such a dependence ($D \approx \lambda u$) means that the relative shock compression density does not grow as the pressure rises, but remains practically constant and equal to the limit density

$$\sigma = \lambda / m (\lambda - 1)$$

The nature of the behavior of the shock compression curves of porous aluminum differs from the other metals investigated: W, Cu, and Mo. In the 6-250 kbar pressure range studied, no compression of the porous material to the state of a solid was determined. At the least pressures achieved in the experiment (6.5 and 12.5 kbar) the porous shock adiabats approach closest to the solid aluminum compression curve for initial densities of $\rho_{00} = 0.9$ and 1.35 g/cm³, however, with a ≈8 and 15% difference in the densities realized. It is not excluded that porous aluminum will be compacted completely even at lower pressures than were achieved in these experiments.

The experimental dynamical adiabats are described satisfactorily by the equations of state proposed in [8, 9] for copper and tungsten above the complete packing pressure, and for aluminum above 6.5 and 12.5 kbar pressures, as is illustrated by the dashed curves in Figs. 3 and 4.

The data obtained for W and Cu (according to the shape of the dynamic compression curves) agree with the results from [1, 2] on the shock loading of porous tungsten with the density $\rho_{00} = 12.64$ g/cm³, and for copper with $\rho_{00} = 6.05$ and 7.04 g/cm³. There are papers [4, 6] whose results diverge from the results in [1] and herein. The reasons for the discrepancy are unclear.

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