SHOCK ADIABATS OF POROUS METALS

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In this paper we investigate the shock compression and also the unloading of shock-loaded metals, taking into account the air in the pore spaces between the grains of continuous metal. We study the range of pressures and temperatures of the air during the shock compression, wherein the contribution of the thermal radiation of the air to the pressure and energy is still unimportant. The experimental results, obtained in the pressure range 40-850 kbar for Ni, Cu, and W, agree within experimental error with calculated data. We give the experimental results for the unloading of porous copper from a pressure state of 485 kbar.

Porous metals, which comprise a collection of metallic grains with air bubbles in the spaces between them, under shock compression can be characterized by mean values of the mass and wave velocities, and also by a mean value of the pressure, which is averaged out between the air and the grains of continuous metal. The material inside the grains is compressed and heated to the temperature and density for the continuous metal at this pressure. Under repeated compression of the air we assume that the first two waves are strong, each of them yielding a compression close to its limiting value. A further compression of the air by subsequent weak waves is not taken into account. We consider states wherein the contribution of thermal radiation of the air is still insignificant. The specific volume of the powder is equal to the sum of the specific volumes of the air and of the continuous metal, each multiplied by its weight fraction. Parameters of the shock adiabat (pressure, mass velocity, compression) for the porous metals Ni, Cu, and W, calculated in this way, agree with the experimental results in the range of 40-850 kbar.

Experimental data for the unloading of porous copper confirms the fact that the unloading process is defined by an isentropic expansion of the compressed grains of the continuous metal. In the pressure range from 485 kbar to ~100 kbar, the volume of the air stays constant, being equal to the volume for the state from which the unloading commenced. This can apparently be explained by the fact that the process involving expansion of the air under these conditions is not an isentropic one owing to the influence of the cooling (and, correspondingly, of the compression) of the air due to heat transfer.

To obtain approximate curves for the shock adiabats of porous materials the authors of [1] proposed to take into account the finite compression of the air filling the voids between the grains of the continuous material. Here it may be assumed that for the shock wave transition time (~1 μsec) between the grains and the air only the pressure is averaged out, thermal equilibrium not being established.

It may be assumed that if the Fourier number $F = a\tau/R^2 \ll 1$, then the process of averaging out the temperatures has not yet commenced. Here a is the thermal diffusivity of the grain material, R is a characteristic length, and τ is a characteristic time of the process, the duration of the shock wave.

Thus, for example, for copper with a characteristic grain dimension in the tens of microns, the Fourier number is on the order of one-tenth; i.e., we can assume, apparently, that in this case the process of temperature averaging has not yet begun. Moreover, the specific volume of the powder is equal to the sum of the specific volumes of the air and of the continuous material, each multiplied by its weight fraction. We

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TABLE 1

	U, km/sec	D, km/sec	u, km/sec	p, kbar	σ
Ni	Al (1.28)	2.92 (0.02)	1.69 (0.003)	185 (1.6)	1.000 (0.007)
	Al (2.12)	4.10 (0.04)	2.46 (0.009)	378 (5.0)	1.050 (0.009)
	Al (2.75)	4.95 (0.03)	3.08 (0.007)	572 (4.7)	1.110 (0.007)
	Cu (0.49)	1.33 (0.01)	0.855 (0.061)	35 (5)	0.993 (0.012)
Cu	Al (1.28)	2.76 (0.02)	1.74 (0.004)	143 (1.3)	0.900 (0.008)
	Al (2.12)	3.92 (0.20)	2.61 (0.013)	304 (21.4)	0.995 (0.092)
	Al (2.75)	4.90 (0.09)	3.32 (0.019)	483 (11.7)	1.031 (0.027)
	Cu (0.49)	1.46 (0.02)	0.73 (0.024)	96 (4.5)	0.930 (0.018)
W	Al (1.28)	2.42 (0.05)	1.21 (0.012)	264 (8)	0.930 (0.010)
	Al (2.12)	3.38 (0.04)	1.84 (0.011)	560 (10)	1.020 (0.007)
	Al (2.75)	4.13 (0.01)	2.28 (0.003)	848 (3.3)	1.039 (0.001)
	Al (2.55)	3.72 (0.02)	2.20 (0.006)	736 (5.9)	1.139 (0.005)

consider air states for which the contribution to the energy and pressure of the thermal radiation is negligible, this contribution being significant for temperatures above a million degrees [2].

The authors of [1] took into account compression of the air by a single shock wave. A much closer agreement with experiment may be obtained if during repeated compression of the air bubbles (which occurs in actuality), the two first waves are assumed to be strong, each of these waves compressing the air close to its limiting value, and if the additional compression by the "weak" waves that follow is negligible.

By analogy with [1] we obtain expressions: for the specific volume V* of the powder:

$$V^* = V + (k-1)\left(\frac{\gamma-1}{\gamma+1}\right)^2 V_0 \tag{1}$$

for the compression:

$$\frac{1}{\sigma^*} = \frac{1}{\sigma} + (k-1)\left(\frac{\gamma-1}{\gamma+1}\right)^2 \tag{2}$$

for the mass velocity:

$$u^* = \left[u^2 + \frac{4\gamma}{(\gamma+1)^2}(k-1)\rho V_0\right]^{1/2} \tag{3}$$

Here V is the specific volume, k is the coefficient of porosity, σ is the compression, taken with relation to the initial specific volume V_0 of the continuous material, u is the mass velocity, p is the pressure, and γ is the exponent of adiabaticity for air.

Quantities bearing the asterisk characterize the powder, quantities without it refer to the continuous material. The expressions (1), (2), and (3), for a known shock adiabat of the continuous material, make it possible for us to construct the shock adiabat of a material of porosity k in (p, u) and (p, σ) coordinates over the range where γ for air stays constant. It was shown in [2] that for $p_1 < 0.56$ kbar, we may take $\gamma_1 = 1.2$ and that for $p_2 > 150$ kbar, we may take $\gamma_2 = 5/3$. We assume that over the intervening range in which the pressure goes from p_1 to p_2, the fraction λ of the air with $\gamma_1 = 1.2$ decreases, i.e., we let

$$\lambda = 1 - p/p_2 \tag{4}$$

We shall assume that $p_1 \ll p_2$. Then

$$\lambda = 1 \quad \text{for } p = p_1, \ \lambda = 0 \quad \text{for } p = p_2$$

As a result we obtain: for the specific volumes

$$V^* = V + (k-1)V_0\left[\lambda\left(\frac{\gamma_1-1}{\gamma_2+1}\right)^2 + (1-\lambda)\left(\frac{\gamma_2-1}{\gamma_2+1}\right)^2\right]$$

for the compressions

$$\frac{1}{\sigma^*} = \frac{1}{\sigma} + (k-1)\left[\lambda\left(\frac{\gamma_1-1}{\gamma_1+1}\right)^2 + (1-\lambda)\left(\frac{\gamma_2-1}{\gamma_2+1}\right)^2\right]$$

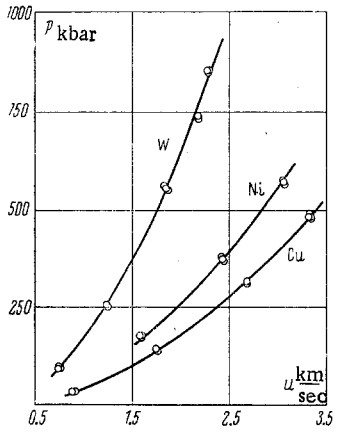

Fig. 1

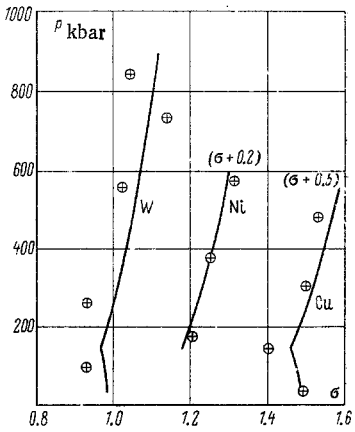

Fig. 2

TABLE 2

	ρ_0, gm/cm³	D, km/sec	u, km/sec	p, kbar
Water	1.0	7.41	3.74	277
		7.36	3.70	272
Plastic Foam	0.80	6.22	3.66	181
		6.21	3.66	174
Plastic Foam	0.51	5.75	4.055	118
		5.72	4.03	116
Plastic Foam	0.196	5.32	4.38	46
		5.31	4.29	44
Air	$1.293 \cdot 10^{-3}$		5.52	0.100
			5.62	0.100

A corresponding expression can also be obtained for the intervening range for the mass velocity.

The unloading process for a shock-compressed porous material may evidently be represented in the following way. The material in the grains of the continuous substance expands along the isentrope from the corresponding state $p^{*\circ}$, $\sigma^{*\circ}$. It is likely that in the air bubbles two competing processes coexist: cooling at the expense of heat transfer and, corresponding to this, a compression of the air, and an isentropic expansion. For the cooling, the decrease in the volume can be taken proportional to the decrease in temperature and to the ratio of the pressures

$$\frac{V_2}{V_2^{*\circ}} = \frac{T_2}{T_2^{*\circ}} \frac{p^{*\circ}}{p}$$

For an isentropic expansion the increase in volume amounts to

$$\frac{V_2}{V_2^{*\circ}} = \left(\frac{p^{*\circ}}{p}\right)^{1/\gamma}$$

We present some of the results of our experiments with porous Ni, Cu, and W, over a range of pressures for which experimental data has as yet not been published, and we compare them with calculated results.

Specimens of porous nickel, copper, and tungsten were prepared with values of density ρ_0 in gm/cm³ and porosity as shown in the parentheses: Ni (3.75, 2.75), Cu (2.97, 3.01), W (9.00, 2.15).

The shock adiabats were obtained by the method of reflection (see [2]) with the aid of four different explosive installations, wherein a shock wave is generated in a standard specimen, this wave then being refracted into the specimen under investigation. To avoid distortion of the shock wave by lateral unloading the ratio of the diameter of the specimen to its height was taken sufficiently large, being varied from 10 to 20 from specimen to specimen. In each separate experiment with a given specimen, up to eight measurements of shock wave velocity in the specimen were obtained. From 2 to 4 experiments for each of the powders were carried out on each of the explosive installations.

The deviation of the initial density of the specimens from nominal did not exceed 1.5% in the experiments. Nevertheless, corrections were introduced into the experimental results taking this deviation of the density into account. The maximum value of the correction did not exceed 1%, and in the majority of cases amounted to several tenths of one percent.

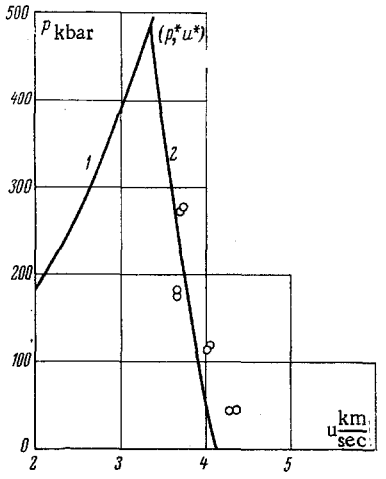

Fig. 3

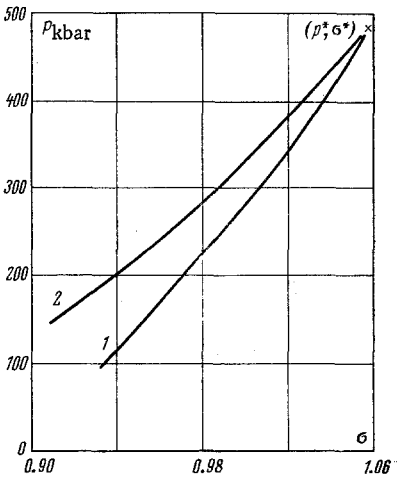

Fig. 4

Table 1 gives the values of the measured shock wave speeds D, with the corrections already taken into account; the second column indicates the standard material and its wave speed U in km/sec. By considering the situation at the contact boundary between the standard material and the porous specimen, where a decomposition takes place in the shock wave speeds, we obtained values of the pressure p, the mass velocity u, and also the compression σ, in the specimen. The quantities in parentheses denote standard error of the measurements. The last three columns for the mass velocity, the pressure, and the compression display standard errors, which were calculated from formulas resulting from the expression for the variance of a function of two variables which are linearly related (see [3]):

$$\varkappa_u = \frac{\varkappa_D}{|m|}, \qquad \varkappa_p = |\varkappa_u + \varkappa_D|, \qquad \varkappa_\sigma = (k\sigma - 1)\,|\varkappa_u - \varkappa_D|$$
$$m = 1 + \frac{\rho_{0s}}{\rho_0^*}\,\frac{c_s + 2\beta_s(2U - u)}{D^*} \tag{5}$$

Here $\varkappa$ is the relative magnitude of the mean-square error, the coefficient of variation [4]; the subscript on $\varkappa$ indicates the physical quantity to which it applies; ρ_0 is the initial density; c and β are the coefficients appearing in the D vs u dependence.

The subscript s indicates that the quantity in question refers to a state in the standard material; the asterisk indicates reference to the porous specimen.

In addition, experiments were carried out to follow the downward trend of the unloading curve of porous copper (k = 3.01) from the state $p^{*\circ} = 485$ kbar. This involved placing, relative to the subsequent path of the shock wave, less rigid materials back of the specimen of porous copper, namely, water and plastic foams of three different densities, the latter labeled PS for polystyrene; the D vs u relations for these materials were obtained by interpolating the experimental data from [5]. An experimental verification confirmed the validity of this interpolation. A measurement of the shock wave speed in these materials made it possible, knowing their shock adiabats, to determine the pressure and mass velocity in the porous copper.

In Table 2 we present the experimental results for the unloading of the porous copper (k = 3.01) from the state $p^{*\circ} = 485$ kbar, $\sigma^{*\circ} = 1.058$, $u^{*\circ} = 3.35$ km/sec; in addition, for air we give the values of the free surface velocity.

In Fig. 1, pressure p in kbar is plotted against mass velocity u in km/sec, the results calculated from formula (3) being displayed by means of continuous curves; in addition we have plotted the experimental shock adiabat data for Ni, Cu, and W. A similar comparison is made on the pressure-compression (relative density σ) plot in Fig. 2. As these curves show, the idea employed here for investigating the shock compression of porous metals by taking into account the air between the solid grains gives good agreement with the experimental results in the p vs u plane and somewhat poorer in the p vs σ plane. The latter can be explained by the large error in the values of σ, which arise in the calculations (see [5]). The available experimental results on the shock compression of porous metals [6-9] in the range of pressures up to 1 Mbar

also confirm the ideas presented above. However, the results given in [6-8] refer, for the most part, to the domain of pressures exceeding 1 Mbar. Under these conditions it becomes necessary to take into account the thermal radiation of the air. The latter apparently has the effect that at some pressure a mean compression of the powder will be realized, which is less than that determined from formula (2), due to vaporization of a part of the metal from the surface of the grains. A comparison of the results given in [6-8] for large pressures qualitatively confirms the validity of this assumption.

The experimental results with respect to the unloading of previously shock-compressed porous copper can be described, as in [8], in terms of pressure and mass velocity by a formula of the form

$$p = a\,(W - u) + b\,(W - u)^2 \tag{6}$$

where

$$a = \rho_0 c_0, \quad b = \rho_0 \beta$$

where ρ_0, c_0, and β are, respectively, the density and the coefficients appearing in the D vs u relationship for the continuous metal; finally, W is the value of the mass velocity at p = 0. The unloading curve in the pressure vs compression variables may be represented as follows:

$$\sigma = \left(\frac{1}{\sigma^{*\circ}} + \frac{\rho_0}{4b} \ln \left| \frac{a^2 + 4bp^{*\circ}}{a^2 + 4bp} \right| \right)^{-1} \tag{7}$$

Here $p^{*\circ}$, $\sigma^{*\circ}$ are the coordinates of the point from which the unloading begins. The validity of formulas (6) and (7) was checked in the case of continuous copper, the unloading curve being calculated from formulas (6) and (7) from the initial state p = 485 kbar, σ = 1.224, and u = 1.0 km/sec, and these calculations were then compared with the isentrope passing through this state, where the isentrope was calculated from a known equation of state with a constant Grüneisen parameter. Complete agreement was obtained between the curve based on Eq. (7) and the isentrope based on the known equation of state.

The experimental results obtained for the unloading of porous copper from the state $p^{*\circ}$ = 485 kbar, $\sigma^{*\circ}$ = 1.058, and $u^{*\circ}$ = 3.35 km/sec are represented by the points plotted in Fig. 3. The shock adiabat for porous copper is identified there by the numeral 1. The continuous curve 2 in this figure is the mirror image with respect to the p axis of the shock adiabat of continuous copper, drawn through the point $(p^{*\circ}, u^{*\circ})$. With the aid of Eq. (7) the unloading curve was obtained in the $p\sigma$ plane (see the curve labeled 1 in Fig. 4). The curve labeled 2 in this figure corresponds to the isentrope calculated from the equation of state with a constant Grüneisen parameter.

An analysis of the results shows that the unloading of the shock-compressed porous copper is determined by an isentropic expansion of the grains of the continuous metal. A result of this same kind was obtained earlier in [8].

In particular, it follows from a comparison of the unloading curve for porous copper (in Fig. 4, the curve 1 is based on Eq. (7) and the experimental data) and the isentrope for the expansion σ of the continuous copper that the volume occupied by the air stays practically constant in the range of pressures from 485 to ~ 100 kbar, being equal there to the value it had at the initial unloading state $p^{*\circ}$, $\sigma^{*\circ}$. Apparently, the two concurrent processes, namely, the isentropic expansion and the compression, resulting from heat conduction, of the air bubbles, compensate each other in their effects. As time passes, it is likely, as far as the decrease in the pressure in the unloading wave is concerned, that the expansion of the air must dominate; this is apparent in the deviation of the unloading curve of the porous metal toward an increase in the mass velocities (and a corresponding decrease in the density). Lower points for the unloading of the copper into the plastic foam, which has a density of $\rho_0 = 0.19$ gm/cm^3, and into air bears witness to this deviation.

LITERATURE CITED

1. I. M. Voskoboinikov, A. N. Afanasenkov, and V. M. Bogomolov, "Generalized shock adiabat for organic liquids," Fiz. Goreniya i Vzryva, 3, No. 4, 585 (1967).
2. Ya. B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena, Academic Press (1968).
3. N. V. Smirnov and I. V. Dunin-Barkovskii, A Short Course in Mathematical Statistics for Engineering Applications [in Russian], Fizmatgiz, Moscow (1959).

4. A. N. Zaidel', Elementary Estimates of Errors in Measurements [in Russian], Nauka, Leningrad (1967).
5. I. P. Dudoladov, V. I. Rakitin, Yu. N. Sutulov, and G. S. Telegin, "Shock compressibility of polystyrene at varying initial density," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 4, 148 (1969).
6. K. K. Krupnikov, M. I. Brazhnik, and V. P. Krupnikova, "Shock compression of porous tungsten," Zh. Exp. Tekh. Fiz., 42, No. 3,675 (1962).
7. S. B. Kormer, A. I. Funtikov, V. D. Urlin, and A. N. Kolesnikova, "Dynamic compression of porous metals and equation of state with variable heat capacity at high temperatures," Zh. Éksper. Teor. Fiz., 42, No. 3, 686 (1962).
8. I. C. Skidmore and E. Morris, "Experimental equation of state data for uranium and its interpretation in the critical region," in Proc. Sympos. on Thermodynamics of Nuclear Materials, Vienna (1962).
9. R. R. Boade, "Compression of porous copper," J. Appl. Phys., 39, No. 12, 5693 (1968).