COMPLIANCE WITH THE ADDITIVITY RULE FOR A NUMBER OF ALLOYS UNDER SHOCK COMPRESSION

A. A. Bakanova, I. P. Dudoladov, and Yu. N. Sumulov

UDC 534.222.2

Results of an experimental investigation of the shock compressibility of four two-component alloys in the 200 kbar to 5 Mbar pressure range are presented. The shock compression curves of these alloys in the pressure range examined agree, within the limits of experimental scatter, with the Hugoniot adiabat computed from the shock adiabats of the components in an additive approximation [1-3].

It is shown that the adiabats constructed additively also describe test results for alloys of iron with nickel, brass, and two chemical compounds, tungsten and tantalum carbides, investigated earlier [4-6].

Up to now the additivity of the thermodynamic parameters has been considered for the high-pressure domain only in application to macroscopic heterogeneous composite states [1-3].

METHOD OF INVESTIGATION AND RESULTS

Alloys of niobium with 5 and 30% tantalum (weight), NT5E and NT30E, respectively, rhenium with molybdenum (40% Mo and 60% Re, weight), and titanium with molybdenum (30% Mo and 70% Ti, weight) were selected as objects of investigation. All the alloys belong to systems forming a continuous series of solid solutions.

The method of reflections, elucidated in detail in [6, 7], was used to determine the shock compression curves of these alloys.

Shock waves of known intensity (P_* is the pressure and U_* the mass flow rate) were applied to aluminum or iron screens covering the samples being investigated. The shock velocities in the specimens studied D were determined in the experiments. The desired thermodynamic characteristics, the pressure, shock compression energy, and density of the material behind the shock front were found by means of the

TABLE 1

Investigated alloy	Screen material	U_*, km/sec	D, km/sec	U, km/sec	P, Mbar	σ	V, cm^3/g
(NT5E) Nb—Ta $\rho_0 = 8.79$ g/cm³	Aluminum	1.51	5.57	0.94	0.46	1.203	0.0947
	Aluminum	2.76	6.57	1.80	1.04	1.377	0.0826
	Iron	2.45	7.27	2.42	1.55	1.499	0.0759
	Iron	4.52	10.23	4.48	4.03	1.779	0.0639
	Iron	2.95	8.07	2.90	2.06	1.560	0.0729
(NT30E) Nb—Ta $\rho_0 = 9.93$ g/cm³	Aluminum	1.51	5.25	0.90	0.47	1.207	0.0835
	Aluminum	2.76	6.35	1.71	1.08	1.368	0.0736
	Iron	2.45	7.06	2.32	1.63	1.489	0.0676
	Iron	4.52	9.92	4.32	4.26	1.771	0.057
Re—Mo $\rho_0 = 14.71$ g/cm³	Aluminum	0.69	5.08	0.26	0.19	1.054	0.0645
	Aluminum	1.51	5.36	0.68	0.54	1.145	0.0591
	Aluminum	2.76	6.24	1.35	1.24	1.276	0.0533
	Iron	2.45	6.95	1.96	2.00	1.393	0.0488
	Iron	4.49	9.36	3.70	5.09	1.654	0.041
Ti — Mo $\rho_0 = 5.24$ g/cm³	Aluminum	1.51	6.06	1.20	0.38	1.247	0.153
	Aluminum	2.76	7.12	2.28	0.85	1.471	0.130
	Iron	2.45	8.03	2.82	1.19	1.541	0.124
	Iron	4.52	10.79	5.26	2.97	1.951	0.098

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 167-172, November-December, 1972. Original article submitted March 31, 1972.

TABLE 2

Alloy name	P, Mbar	V_2, cm^3/g	V_1, cm^3/g	$\frac{V_1-V_2}{V_2}$, %
Brass [6] $\rho_0 = 8.44$ g/cm^3	0	0.1184	0.1216	2.7
	0.25	0.1024	0.1032	0.8
	0.50	0.0942	0.0945	0.3
	1.0	0.0842	0.0855	1.5
	1.5	0.0788	0.0800	1.5
	2.0	0.0748	0.0760	1.5
Iron-nickel alloy [5] (Ni — 18%, weight) $\rho_0 = 7.96$ g/cm^3	0	0.1257	0.1247	1
	0.5	0.0992	0.0982	1.0
	1.0	0.0923	0.0915	0.9
	1.5	0.0870	0.0865	0.6
	2.0	0.0828	0.0824	0.5
Iron-nickel alloy [5] (Ni — 26%, weight) $\rho_0 = 7.97$ g/cm^3	0	0,1255	0.1236	1.5
	0.5	0.0994	0.0978	1.6
	1.0	0.0920	0.0909	1.2
	1.5	0.0866	0.0860	0.7
	2.0	0.0821	0.0823	0.2
Iron-silicon alloy [15] (Si — 4%, weight) $\rho_0 = 7.646$ g/cm^3	0	0.1309	0.1394	—
	0.5	0.1058	0.1074	1.5
	1.0	0.0959	0.0981	2.3
	1.5	0.0898	0.0925	2.7
	2.0	0.0864	0.0897	3.8
Iron-silicon alloy [15] (Si — 19.8%, weight) $\rho_0 = 7.016$ g/cm^3	0	0.1426	0.1865	—
	0.5	0.1202	0.1297	7.9
	1.0	0.1091	0.1189	9.0
	1.5	0.1007	0.1132	12.4
	2.0	0.0950	0.1097	15.5

values of D in the specimens, and the parameters P_* and U_* by using the mass and momentum conservation laws and the condition that the pressures and velocities were equal on the specimen–screen interface. The pressures realized in the alloys under investigation were produced by using the explosive apparatus described in [8, 9].

The shock compression characteristics in the studied alloys which were recorded in the tests are presented in Table 1. The table shows the initial density ρ_0 and wave velocity D in the specimens and their corresponding mass flow rates U, dynamic compression pressure P, relative compression $\sigma = \rho/\rho_0$, specific volume V, and the screen material and the mass flow rates U_* therein.

The dynamical adiabats of iron and aluminum used as screens are described in D–U coordinates by the relationships [8, 10]:

$$D = 5.25 + 1.39U \text{ (Al)}, \qquad D = 3.85 + 1.615U \text{ (Fe)}$$

DISCUSSION OF RESULTS

The test results obtained are shown graphically on the wave–mass flow rate diagrams in Fig. 1 (1 and 2 are for Re–Mo and Ti–Mo alloys, 3 and 4 are for the Nb–Ta alloys NT5E and NT30E, respectively; the dashes are extrapolated portions of the D–U relationships).

The experimental results in D–U coordinates are described by the following linear relationships, whose coefficients were determined by least squares.

We have D=4.00+1.365U, D=4.53+1.289U, and D=4.60+1.176U for the alloys NT30E, Re–Mo, and Ti–Mo, respectively.

For the alloy NT5E they are located on two lines of different slope:

$$D = 4.48 + 1.157U \quad (0 \leqslant U \leqslant 2.45), \quad D = 3.81 + 1.430U \quad (2.45 \leqslant U \leqslant 4.5)$$

The Hugoniot adiabats computed from these D–U dependences are shown by solid lines in the P–V diagrams (Fig. 2).

In studying the niobium–tantalum alloys for two relationships between the components, it was proposed to clarify the influence of the magnitude of the tantalum admixture on the rearrangement of the electron configuration, determined in the niobium, which occurred under the effect of high pressure [10, 11].

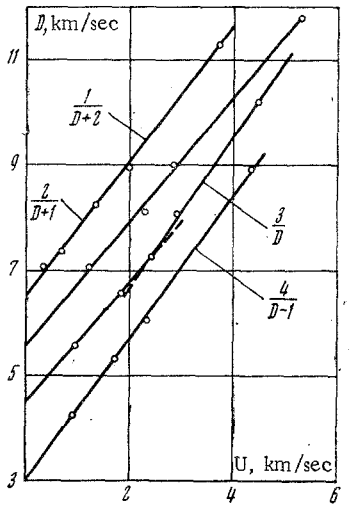

Fig. 1

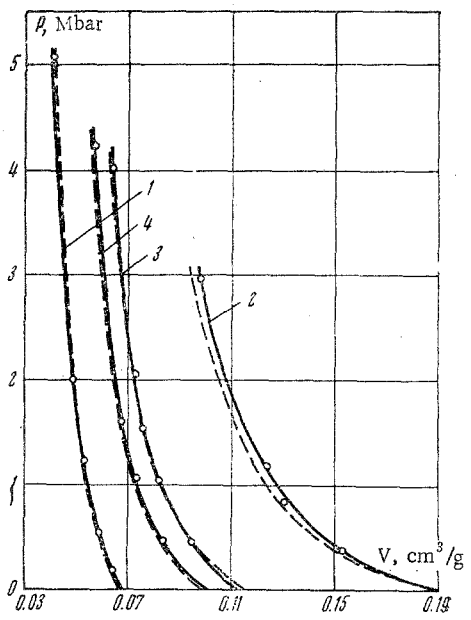

Fig. 2

The presence of a breakpoint characteristic for metals experiencing electron transitions in the D–U dependence for the alloy with 5% tantalum, and its absence in the alloy with 30% tantalum, indicate that a small admixture of tantalum (5%) to niobium does not alter the nature of compression. A breakpoint accompanied by a diminution in compression is observed on the adiabat of the NT5E alloy as on niobium.

The admixture of 5% Ta to Nb alters somewhat the critical parameters for which the electron transition is accomplished. They are $P^* = 1.55$ Mbar, $U^* = 2.45$ km/sec for the NT5E alloy, and $P^* = 860$ kbar, $U^* = 1.62$ km/sec for Nb according to [10].

It should be noted that these parameters are less definite for the NT5E alloy than for Nb because of the smaller number of experiments.

Under the assumption that the rule of additivity is conserved in alloys exactly as in mechanical mixtures [1, 2], curves of the dynamical adiabats were computed by means of the relationship

$$V_{12}(P) = \alpha_1 V_1(P) + (1 - \alpha_1) V_2(P) \tag{1}$$

Here α_1, $(1-\alpha_1)$ are the weight concentrations of the first and second members of the alloy, $V_1(P)$ and $V_2(P)$ are the specific volumes of the first and second constituents of the alloy in the individual shock adiabats of the metal specimens under the pressure P, and $V_{12}(P)$ is the specific volume of the alloy under the pressure P.

An identical degree of compression of each constituent is assumed in this approximation for a separate shock compression in monolithic specimens and in alloys under identical pressures.

The additive adiabats of alloys computed by means of (1) are shown in Fig. 2 by dashes. The shock compression curves of the alloy constituents Ta, Nb, Ti, Mo, Re have been published in [6, 10-13].

Adiabats of these metals are approximated on the D–U diagrams by relationships of the form

$$D = C_0 + \lambda U \tag{2}$$

Ta ($\rho_0 = 16.38$ g/cm^3),	$D = 3.29 + 1.326U$	$(0 < U < 6.0)$
Nb ($\rho_0 = 8.58$ g/cm^3),	$D = 4.70 + 0.920U$	$(0 < U < 1.62)$
	$D = 3.91 + 1.409U$	$(1.62 < U < 4.5)$
Ti ($\rho_0 = 4.50$ g/cm^3),	$D = 4.81 + 1.126U$	$(0 < U < 9.5)$
Mo ($\rho_0 = 10.20$ g/cm^3),	$D = 5.14 + 1.267U$	$(0 < U < 7.0)$
Re ($\rho_0 = 21.02$ g/cm^3),	$D = 4.03 + 1.414U$	$(0 < U < 4.0)$

As Fig. 2 shows, agreement holds between the curves computed in the additive approximation and the test adiabats for three of the investigated alloys in the whole pressure range studied.

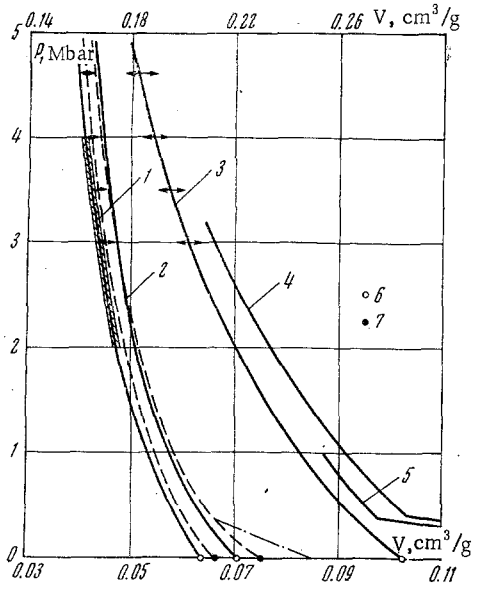

Fig. 3

A small discrepancy between the computed and experimental results (~3%) is observed in the 3 Mbar pressure range for the Ti–Mo alloy. However, this difference does not emerge beyond the boundaries of the probable errors due to experimental inaccuracies in the adiabats of the alloy and of the constituents.

The possibility of satisfying (1) was also verified for two chemical compounds [tungsten carbide (WC) and tantalum carbide (TaC)] and the alloys [iron with nickel (10% and 26% Ni, by weight), iron with silicon (4% and 19.8% Si, by weight) and brass]. The behavior to a 5 Mbar pressure under shock compression has been traced in [4] for TaC and WC, and in [5, 6, 14] for the alloys mentioned.

The solid lines 1 and 2 in Fig. 3 represent the dynamical adiabats of WC (1) and TaC (2) according to [4], together with the additive adiabats (dashes) found by substituting the Ta volumes from (2) into (1), the W from [6, 15, 16], and the carbon taken from [17]. According to (2) the shock adiabats for W and diamond are

$$W\ (\rho_0 = 19.17\ \text{g/cm}^3)\ D = 3.97 + 1.27U \quad (0 < U < 4.0)$$
$$\text{Diamond}\ (\rho_0 = 3.51\ \text{g/cm}^3),\ D = 12.16 + 1.00 \quad (0 < U < 8.0)$$

The shock compression curve of the light constituent of these compounds, carbon, should especially be established.

The shock compressibility of both carbon modifications were investigated in [17, 18], diamond to ~6 Mbar pressures, and graphite to ~3 Mbar. The history of the diamond and graphite compression curves with two different initial densities ρ_{00} is shown in the right side of Fig. 3 by the curves 3-5 (3 is diamond from [17], 4 and 5 are graphite from [18], respectively, for ρ_{00} = 1.75-1.85 g/cm³ and ρ_{00} = 2.23 g/cm³).

The upper scale in Fig. 3 refers to graphite and diamond, and the lower to WC and TaC. The experimental adiabat of diamond, traced up to high pressures, was taken as the light component in computing the shock compression curves for TaC and WC by means of (1). As the computations showed, use of the "diamond" portion of the shock adiabat of graphite [18] with ρ_{00} = 2.23 g/cm³, close to the crystallographic value (ρ_0 = 2.26 g/cm³), results in an insignificant shift in the computed curve towards high specific volumes by the very small value ΔV = 0.0006-0.0003 cm³/g.

As follows from the graph for TaC, at pressures above 1 Mbar an exact description of the experiment by the additive curve constructed by means of the tantalum and diamond adiabats holds. For tungsten carbide, the difference between the additively constructed and the test curve is ~3% in volume in the whole pressure range.

At a pressure below the phase transition of graphite (P < 390 kbar), the additive adiabat of TaC differs by 6% from the experimental. Let us note that if the graphite rather than the diamond adiabat is used as the shock adiabat of the light component, a sharp deflection is observed on the computed curve shown by a dash-dot line for TaC in Fig. 3. The arrows in Fig. 3 show the boundaries of the probable experimental scatter of the adiabat of the analysis and the probable errors in the location of the additive adiabat of WC due to inaccuracies of the adiabats of the components. The hatched section is the probable errors of the experimental compression curve for WC, and curves 6 and 7 are the initial specific volumes of the real materials and that computed from the adiabat of the light component, diamond, from (1) [17].

The results of comparing the additive shock adiabats for the alloys Fe–Ni (10 and 26% Ni, by weight), Fe–Si (4 and 19.8% Si and 0.3-0.4% W for both alloys), and brass (composition by weight Cu : Zn : Pb : Fe = 61,5 : 36 : 0.25 : 0.05) with the experimental adiabats obtained in [5, 6, 14] are represented in Table 2. (Here V_1 and V_2 are the computed and experimental volumes.) The dynamic adiabats needed for the components of these alloys are presented in [19, 20].

Comparison of the computed and test results for the alloys (Table 1) shows that the additive principle of the computation is only violated here for the Fe–Si alloys whose computed adiabat differs by 7-13% from experiment [14] for the alloy with 20% Si and by 3% for the alloy with 4% Si. The deviation of the prognosticated curves from the experimental is 1% on the average for the brass and iron-nickel alloys. It is difficult to answer unambiguously to what the significant discrepancy for the iron-silicon alloys is due.

The results of the investigations performed showed that for a number of alloys and chemical compounds, exactly as for mixtures and solutions [1, 2, 21], the Hugoniot adiabat can be determined sufficiently accurately by computations by starting from the shock compressiblity of the individual components. It would be interesting later to extend similar investigations considerably to a whole series of other chemical compounds and alloys.

LITERATURE CITED

1. A. N. Dremin and I. A. Karpukhin, "Method of determining the shock adiabats for disperse materials," Zh. Prikl. Mekh. i Tekh. Fiz., No. 3 (1960).
2. Yu. F. Alekseev, V. P. Krupnikova, and L. V. Al'tshuler, "Shock compression of two-component paraffin–tungsten mixtures," Zh. Prikl. Mekh. i Tekh. Fiz., No. 3 (1971).
3. L. V. Al'tshuler and I. I. Sharipdzhanov, "Additive equations of state of silicates at high pressures," Izv. Akad. Nauk SSSR, Fiz. Zemli, No. 3, 11 (1971).
4. M. N. Pavlovskii, "Shock compressibility of six highly solid materials," Fiz. Tverd. Tela, 12, No. 7 (1970).
5. R. G. McQueen and S. P. Marsh, "Shock-wave compression of iron-nickel alloys and the earth's core," J. Geophys. Res., 71, No. 6 (1966).
6. R. G. McQueen and S. P. Marsh, "Equation of state for nineteen metallic elements for shock-wave measurements to two megabars," J. Appl. Phys., 31, No. 7 (1960).
7. L. V. Al'tshuler, K. K. Krupnikov, and M. I. Brazhnik, "Dynamic compressibility of metals at pressures from 400,000-4,000,000 atm, "Zh. Eksp. Teor. Fiz., 34, No. 4 (1958).
8. L. V. Al'tshuler, S. B. Kormer, A. A. Bakanova, and R. F. Trunin, "Equations of state of aluminum, copper, and lead for the high-pressure domain," Zh. Éksp. Teor. Fiz., 38, No. 3 (1960).
9. L. V. Al'tshuler, M. N. Pavlovskii, L. V. Kuleshova, and G. V. Simakov, "Investigation of halogens of the alkali metals at the high pressures and temperatures of shock compression," Fiz. Tverd. Tela, 5, No. 1 (1963).
10. L. V. Al'tshuler, A. A. Bakanova and I. P. Dudoladov, "Influence of the electron configuration on compressibility of metals at high pressure," Zh. Éksp. Teor. Fiz., 53, No. 6 (1967).
11. L. V. Al'tshuler and A. A. Bakanova, "Electron configuration and compressibility of metals at high pressures," Usp. Fiz. Nauk, 96, No. 2 (1968).
12. K. K. Krupnikov, A. A. Bakanova, M. I. Brazhnik, and R. F. Trunin, "Investigation of the shock compressibility of titanium, molybdenum, tantalum,and iron," Dokl. Akad. Nauk SSSR, 148, No. 6 (1963).
13. J. M. Walsh, M. H. Rice, R. G. McQueen, and F. L. Yarger, "Shock-wave compressions of 27 metals. Equations of state of metals," Phys. Rev., 108, No. 2 (1957).
14. A. S. Balchan and G. K. Cowan, "Shock compression of two iron–silicon alloys to 2.7 Mbars", J. Geophys. Res., 71, No. 14 (1966).
15. K. K. Krupnikov, M. I. Brazhnik, and V. P. Krupnikova, "Shock compression of porous tungsten," Zh. Éksp. Teor. Fiz., 42, No. 3 (1962).
16. A. H. Jones, W, M. Isbell, and C. J. Maiden, "Measurement of very-high pressure properties of materials using a light-gas gun," J. Appl. Phys., 37, No. 9 (1966).
17. M. N. Pavlovskii, "Shock compression of diamond," Fiz. Tverd. Tela, 13, No. 3 (1971).
18. M. N. Pavlovskii and V. P. Drakin, "On the question of the metallic phase of carbon," ZhÉTF Pis. Red., 4, No. 5 (1966).
19. L. V. Al'tshuler, A. A. Bakanova, and R. F. Trunin, "Shock adiabats and zero isotherms of seven metals at high pressures," Zh. Éksp. Teor. Fiz., 42, No. 1 (1962).
20. M. N. Pavlovskii, "Formation of metallic modifications of germanium and silicon under shock compression conditions," Fiz. Tverd. Tela, 9, No. 11 (1967).
21. L. V. Al'tshuler and M. N. Pavlovskii, "Investigation of clays and clay shale under strong dynamical effects," Zh. Prikl. Mekh. i Tekh. Fiz., No. 1 (1971).