MELTING AND EVAPORATION OF METALS IN AN UNLOADING WAVE

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The thermodynamic states resulting in melting and evaporation in an isentropic expansion wave during dissociation are computed for sixteen metals. Semiempirical equations of state of the condensed phase and tabulated data on the melting and evaporation entropies are used.

The realization of a number of prospective engineering projects and apparatus (laser heating [1], linear pinch [2], magneto-cumulative generators [3, 4], apparatus for "soft" magnetic compression [5], etc.) is based on the attainment of extremal parameters by means of a high energy concentration. Information about the thermophysical properties, primarily data about the phase composition of a substance in an unloading wave, is needed to analyze and compute the hydrodynamic phenomena evoked by the dissociation of such high-energy states.

The processes under consideration can be analyzed within the framework of the following scheme: fast energy liberation (in the shock front, in the skin layer, etc.) in the condensed phase with a subsequent expansion of the substance in an isentropic unloading wave. In conformity with this scheme, the states resulting in melting and evaporation of the substance during dissociation are computed on the basis of semiempirical equations of state for the condensed phase.

Here evaporation is understood to be the transition of the substance into a low density state $\rho \leqslant \rho_c \approx {}^1/_3\rho_0$ (ρ_0 is the density of the solid, and ρ_c is the density of the substance at the critical point). Keeping in mind the shock method of generating high-energy states, which affords the possibility of conducting an experimental investigation of the thermophysical properties of metals within a wide phase-state range from a strongly compressed condensed state to a gaseous (plasma) domain, the shock parameters, and the characteristics of the explosive dynamic-loading units permitting the realization of the selected parameter band are computed.

The density range ${}^1/_5\rho_0 \leqslant \rho \leqslant \rho_0$ is characterized for metals by a small quantity of experimental material and an uncertainty in the theoretical predictions [6], which does not afford a possibility of carrying out direct calculations of the expansion isentrope under these conditions. An entropy criterion [7], taking account of the condition of flow isentropy in an unloading wave and based on comparing tabulated values [8] of the phase transformation entropies at atmospheric pressure with the condensed-phase entropies of metals in the high pressure and temperature range [9], was used in the computations.

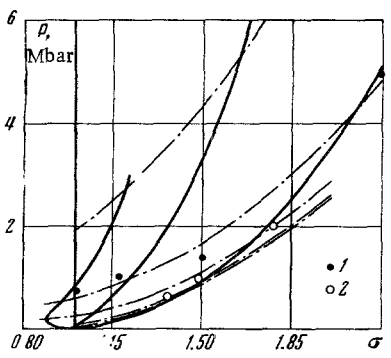

Fig. 1

The condensed-phase entropy was computed by using semiempirical equations of state, constructed on the basis of experimental results on the shock compression of metals. Detailed computations were carried out for Al, Ni, Cu, Pb for which there exists the most developed equation of state describing the data on shock compression of continuous and porous specimens in a broad range of densities and having an ideal gas asymptotic at high temperatures [10]. [The use of the Mie–Gruneisen equation of state outside the domain of its validity in [11] led the author to an erroneous deduction about the exist-

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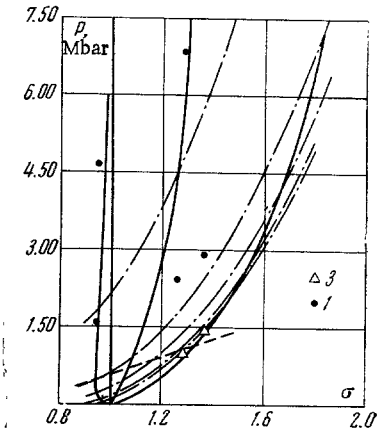

Fig. 2

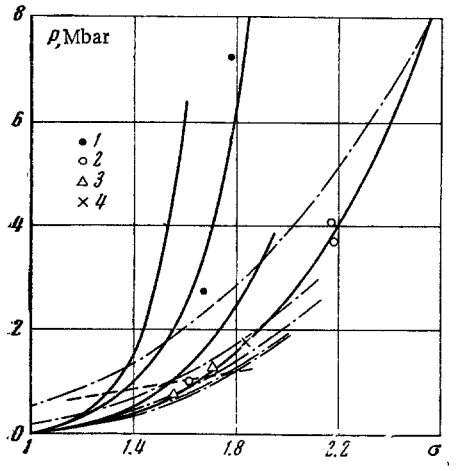

Fig. 3

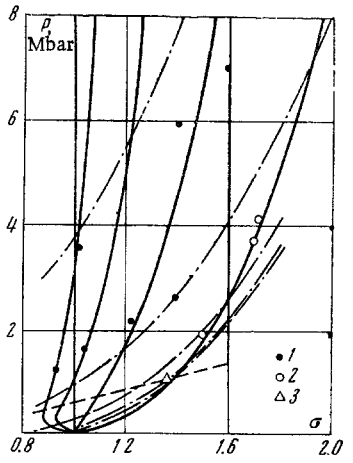

Fig. 4

ence of an entropy maximum on the single charge line (i.e., the intersection of the entropy and this line at two points), which clearly contradicts experiment [10].]

$$p = p_* + \frac{3\gamma + z}{1+z}\rho R(T - T^*) + g\rho\frac{b^2}{\beta}\ln \operatorname{ch}\frac{\beta T}{b},$$
$$E = E_* + \frac{2+z}{1+z}\frac{3}{2}R(T - T^*) + \frac{b^2}{\beta}\ln \operatorname{ch}\frac{\beta T}{b}$$
$$p_* = \sum_i^7 a_i\sigma^{i/3+1}, \quad z = \frac{lRT}{C_*^2}, \quad T^* = E_0 - \frac{T_0}{C_v}$$
$$C_*^2 = \partial p_*/\partial\rho, \quad \sigma = \rho/\rho_{0k}, \quad g = -d\ln\beta/d\ln\rho \qquad (1)$$

Here p_*, E_* are the pressure and internal energy on the T = 0 isotherm, γ is the Gruneisen coefficient, β is the coefficient of electronic specific heat, and b, l, a_i are empirical constants (see [10]).

The equation of state (1) results in an entropy equation

$$S = S_0 + R\int_{v_0}^{v}\frac{3\gamma + z_0}{1+z_0}\frac{dv}{v} + bg\int_{v_0}^{v}\operatorname{th}\frac{\beta T}{b}\frac{dv}{v} + b\int_{T_0}^{T}\frac{1}{T}\operatorname{th}\frac{\beta T}{b}dT +$$
$$+\frac{3}{2}R\left[\frac{z_0 - z}{(1+z)(1+z_0)} + \ln\frac{T^2}{T_0^2}\frac{(1+z_0)}{(1+z)}\right], \quad z_0 = \frac{lRT^*}{C_*^2} \qquad (2)$$

which was used to compute the isentrope in the domain of applicability of (1). The values of the entropy S_0 under normal conditions, as well as the entropies corresponding to melting and boiling (S_1, S_2, S_3, S_4 are the entropies corresponding to the beginning and ending of melting and boiling) at atmospheric pressure, are taken from the handbook [8]. The entropy at the critical point S_k was given taking account of an estimate based on the principle of corresponding states.

The results obtained for Al, Ni, Cu, Pb are presented in Figs. 1, 2, 3, and 4, where the Hugoniot adiabats for a different porosity $m = \rho_0/\rho_{00}$ (ρ_{00} is the metal density ahead of the shock front), as well as experimental results [10, 12-14] (1, 2, 3, and 4, respectively), are shown in addition to the isentropes S_1, S_2, S_3, S_k, and S_4, denoted by dash-dot lines, in order of increasing pressure. The states behind the shock front which originate during collision between the aluminum pellet, accelerated to a velocity of $\omega = 5.92$ km/sec by the explosion products, and the target are marked by dots in Figs. 1-4.

An increase in the initial porosity at $\omega = \text{const}$ results in a pressure reduction in the shock front. The entropy on the single-charge line grows substantially as the porosity increases, which permits effective expansion of the phase-state domain accessible for a dynamic experiment, and being limited to linear generators of powerful shocks for this purpose [9]. A broad band of parameters from the condensed to the ideal-gas states (Fig. 5) including the domain of the critical point and the dense strongly nonideal plasma [15], which is not accessible to experiment, is covered by the unloading adiabats.

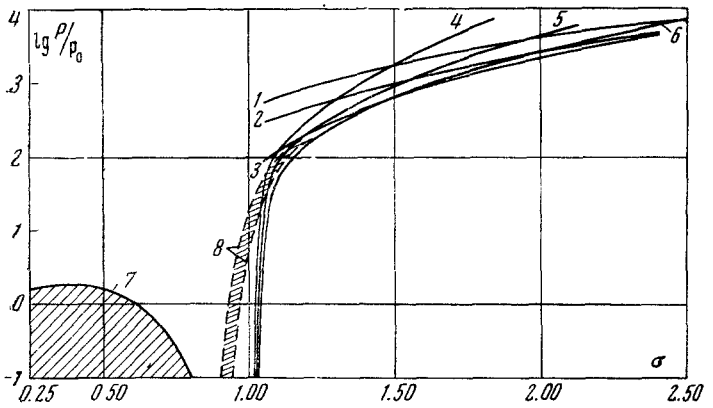

Fig. 5

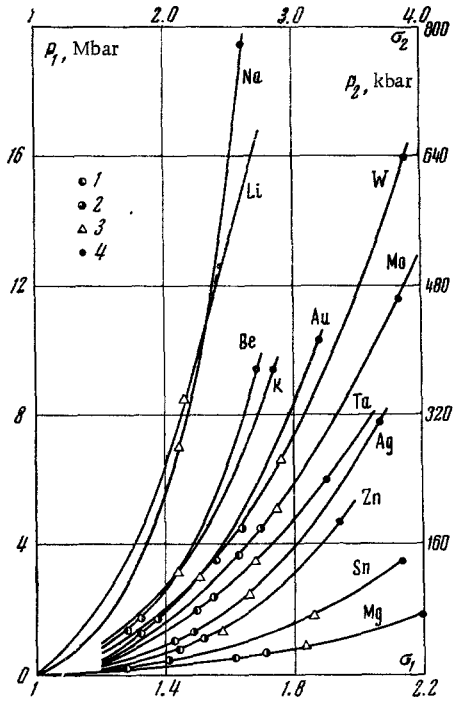

Fig. 6

Represented as an example in Fig. 5 is the phase diagram of lead (the two-phase domains are shaded). The melting curve 8 is shown in conformity with [16]. The shock adiabats m = 1.67, 1.25, 1, presented in Fig. 5 and denoted by 4, 5, and 6, respectively, and the isentropes S_4, S_k, and S_3 (curves 1, 2, and 3) were computed by means of (1) and (2).

The equation of state [17] based on experimental results of shock compression of a continuous material and valid only in the neighborhood of the Hugoniot adiabat m = 1

$$P = P_* + \gamma C_v \rho_{0k} \sigma (T - T^*) + {}^1/_4 \rho_{0k} \beta_* \sigma^{1/2} T^2, \qquad (3)$$
$$E = E_* + C_v (T - T^*) + {}^1/_2 \beta_* \sigma^{-1/2} T^2$$

$$S = S_0 + 3R \int_1^{\sigma} \frac{\gamma(\sigma)}{\sigma} d\sigma + 3R \ln \frac{T}{T_0} + \beta_* \sigma^{-1/2} (T - T_0) \qquad (4)$$

was used in computing the parameters of the rest of the elements considered here.

The results of the computation are presented in Fig. 6, where 1 is the beginning of melting, 2 is the end of melting, 3 is the beginning of boiling, 4 is the critical point, σ_2, P_2 are, respectively, the degree of compression and the pressure for Na, K, Li; σ_2, P_1 are the degree of compression and pressure for Be;

and σ_1, P_1 are the degree of compression and pressure for the remaining elements. It is seen that with the exception of the alkaline metals, which have relatively low values of the critical parameters, shock generators with sufficiently high parameters are needed to realized the states in the near- and post-critical domains, and only application of porous specimens permits the use of existing linear explosive apparatus in the experiment.

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