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PHYSICS

1966

SovietRxiv

## Abstract

## Full Text

UDC 531.66.001.11

*PHYSICS*

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# ON THE MELTING OF LEAD IN A SHOCK WAVE

*(Presented by Academician B. P. Konstantinov, 13 XII 1965)*

Melting in a shock wave, like any other first-order phase transition, must lead to the appearance of two points of inflection on the shock adiabat of the substance ($^1$). The shock adiabat of a substance expanding upon heating is schematically shown in Fig. 1a by the broken line $OABN$. Both in the region of the two-phase state (segment $AB$) and in the region of the liquid state (branch $BN$), the shock adiabat of a substance expanding upon heating must deviate from the shock adiabat of the solid phase (curve $OAmbn$) toward higher values of the specific volume. This conclusion, taking into account the fact that melting of a substance is always accompanied by an increase in its entropy ($^2$), follows directly from the well-known thermodynamic identity ($^3$)

$$\left(\frac{\partial V}{\partial s}\right)_p = -\frac{T}{c_p}\left(\frac{\partial V}{\partial T}\right)_p, \tag{1}$$

where $p$ is pressure, $V$ is specific volume, $s$ is entropy, $T$ is temperature, and $c_p$ is the heat capacity at constant pressure. For some metals, as applied to the region of the two-phase state, the conclusion formulated above was obtained earlier in another way ($^4$).

It follows from Fig. 1a that the distribution of pressures $p$ (as well as densities $\rho = 1/V$ and mass velocities $u$) in a shock wave in the case when $p > p_A$ must have the form schematically shown in Fig. 1b ($^5$). The size $\Delta x$ of the zone in which the pressure changes from $p_m = p_m$ to $p_M = p_M$ must be determined by the time $\tau$ characteristic of melting of the substance in the shock wave (the relaxation time of the phase transition): $\Delta x = D\tau$, where $D$ is the shock-wave velocity. In this case, by virtue of the conservation laws for matter and momentum, the state of the substance in the indicated zone must be described by a point running along the segment of the straight line $mM$ in Fig. 1a ($^1$). The thermodynamic parameters of the substance in the states represented by the points $m$ and $M$ must obviously satisfy the relation

Fig. 1

Figure 1: Fig. 1

$$p_m(V_0 - V_m) - p_M(V_0 - V_M) = u_m^2 - u_M^2 = a\lambda, \tag{2}$$

where $\lambda$ is the specific heat of fusion and $a$ is a coefficient depending on the pressure in the shock wave: $a = 0$ for $p_m \leq p_A$, $0 < a < 1$ for $p_A < p_m < p_b$, and $a = 1$ for $p_m \geq p_b$.

Calculated (6) and experimental (7) estimates indicate that the specific work $p_m(V_0 - V_m) = u_m^2$ for $p_m \geq p_A$ is at least 15-20 times greater than the specific heat of fusion. According to relation (2), this means that the change in the thermodynamic parameters of the substance in the shock wave due to melting cannot exceed ~ 2-3%. Consequently, the conclusion about the mutual arrangement of the shock adiabats of a substance expanding upon heating in the solid and two-phase (as well as liquid) states cannot be experimentally verified by the known methods based on measuring wave and mass velocities (1, 6, 8). To verify the conclusion experimentally, one must turn to other methods. Below a brief account is given of these methods and of the results of experiments with lead. As a ···

lead was chosen as the object of study because, being a typical representative of substances that expand upon heating, it is at the same time characterized by a relatively low melting temperature (327°), a relatively small heat capacity (0.03 cal/g · deg), and has no polymorphic transformations.

The position of the kink point $A$ (Fig. 1a) for a number of low-melting metals was determined in (7) by observing the phenomena arising when a thin aluminum disk strikes a massive ( "semi-infinite" ) target made of the material under study in plane impact. In particular, it was established that the mass velocity in the shock wave that causes melting of lead is ~ 650 m/sec.

**Fig. 1.** Shock adiabat of a substance expanding upon heating, with features due to melting in a shock wave (a), and pressure distribution in a shock wave at $p > p_A$ (b).

A close result is obtained by studying the behavior of the "plug" knocked out of a thin plate of the material under study when a massive cylinder strikes it normally in plane impact. In setting up the experiments it was expected that, if the material of the plate remains in the solid state after impact, then in the free motion of the boundary of the "plug" and of the fragments arising along its perimeter, they should have sharp outlines. If, however, under shock loading the material of the plate melted or began to melt, then in free motion the contours of the "plug" should become blurred, and a jet-like flow should arise along its perimeter subjected to lateral unloading.

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

**Fig. 2.** Radiographs characterizing the state of the "plug" knocked out of a lead plate 2 mm thick at impact velocities of 1085 (a), 1200 (b), 1340 (c), and 1570 m/sec (d). In all cases the states were recorded at $\sim$ 40 mm from the initial position of the lead plate.

The experiments were carried out on a pulsed X-ray installation that made it possible in each experiment to obtain four frames of the process under study with a frame exposure time of $\sim 0.2$ $\mu$sec.

Figure 2 presents radiographs characterizing the process arising when the end face of a copper cylinder (diameter 15 mm, height 9 mm) strikes a lead plate 2 mm thick. The radiographs demonstrate that the behavior of the "plug" knocked out of the plate undergoes the expected change at an impact velocity of $\sim 1250 \div 1300$ m/sec, which corresponds to a mass velocity in the shock wave of $\sim$ 700 m/sec (6, 8).

Thus, the data of (7) and the results of the experiments just described make it possible to consider that melting of lead in a shock wave occurs when the mass velocity reaches $\sim 650 \div 700$ m/sec. This velocity corresponds to a pressure of $\sim 230 \div 250$ thousand atm and a change in specific volume of $\sim 22 \div 23\%$ (6, 8).

The method of a plane impact on a thin plate also makes it possible to verify experimentally the validity of the configuration shown in Fig. 1a. As was said above, if the configuration shown in Fig. 1a is valid (for substances that expand upon heating), then for $p > p_A$ the pressure distribution in the shock wave should have the form presented in Fig. 1b. In a plane impact on a thin plate of the substance under study, such a pressure distribution should cause delamination of the knocked-out "plug" : on the side of the free surface (i.e., on the side that did not receive the impact), a "spall plate" should separate from it ([1,9]).

**Fig. 3.** Radiographs characterizing the process of delamination of the "plug" knocked out of a lead plate 1 mm thick at an impact velocity of 1340 m/sec. The states were recorded 15 (a), 30 (b), 45 (c), and 54 $\mu$sec (d) after the instant of collision of the bodies.

When setting up the experiments it must be borne in mind that, apparently, the separation of the "plate" can be clearly recorded only when the material of the plate still has appreciable tensile strength and when the relaxation time $\tau$ is still sufficiently large. In other words, the impact velocity should be chosen

Fig. 4

Figure 4: Fig. 4

so that the pressure in the shock wave arising in the plate when the colliding bodies meet exceeds the pressure $p_A$ only slightly. In this case the thickness of the "spall plate" should be of the order of $\Delta x/2$ ($^{1,9}$).

The experiments were carried out with copper cylinders and with lead plates 1, 2, and 3 mm thick. The impact velocity was set equal to 1340 m/sec. At this collision velocity the shock wave arising in the impacted plate is characterized by a particle velocity $u \simeq 730$ m/sec and a pressure $p \simeq 260$ thousand atm. ($^{6,8}$).

By means of pulsed X-ray photography, delamination of the "plug" was detected in experiments with plates 1 mm thick (Fig. 3). Measurements showed that the difference in the velocities of the "spall plate" and of the remaining mass of the "plug" is $\sim 3\%$, which agrees well with the estimate following from relation (2).

As for plates 2 and 3 mm thick, in the first experiments it was not possible to record the delamination of the "plug" knocked out of them, and this is naturally connected with the fact that the "plug" (and the gap between the separated parts of the "plug" ) is screened around its perimeter by certain masses of lead, the larger the thicker the plate receiving the impact. However, in experiments with plates of the two indicated thicknesses, the gap between the separated parts of the "plug" was made "visible" by means of a thin (0.05 mm) aluminum foil placed in the path of the "plug," parallel to the lead plate, at a distance of 2–3 mm from it (Fig. 4b–4d). The experiments showed that the foil not only weakens the screening but, imparting a certain impulse to the separated parts of the "plug," even somewhat accelerates the growth of the gap between them.

It is noteworthy that in experiments with plates of different thicknesses the "spall plates" at the corresponding instants of time have one and the same thickness (Fig. 4b–4d). At times close to the beginning of the process, this thickness is $\sim 0.5$ mm. Consequently, one could expect that

upon impact on a lead plate 0.5 mm thick, stratification of the "plug" should not be observed, since in this case the entire "plug" should constitute a "spall plate." Experiments carried out without foil and with foil confirmed this expectation (Fig. 4a).

In addition, experiments were carried out (with foil and without foil) at such impact velocities as lead to the formation in the lead plate of a shock wave with pressure $p < p_A$ and with pressure $p \geq 1.5 p_A$.

**Fig. 4.** Radiographs characterizing the state of the "plug" knocked out of lead plates 0.5 (a), 1 (b), 2 (c), and 3 mm (d) thick at an impact velocity of 1340 m/sec in experiments without foil (upper row of images) and in experiments

with foil (lower row of images). In all cases, the states were recorded $\sim 15$ $\mu$sec after the moment of contact of the bodies.

As expected, in these experiments no stratification of the "plug" was recorded.

Thus, the experimental data obtained make it possible to assert that the mutual arrangement of the shock adiabats of lead (and, in general, of substances that expand upon heating) in the solid and two-phase (as well as in the liquid) states must be precisely that shown in Fig. 1a.

The data obtained also make it possible to estimate, in order of magnitude, the relaxation time $\tau$. Since the experiments have established that $\Delta x/2 \simeq 0.5$ mm, and it is known that under the conditions of the experiments carried out $D \simeq 3$ km/sec ([6,9]), the relaxation time is

$$\tau = \Delta x/D \simeq 3 \cdot 10^{-7} \text{ sec.}$$

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Received
27 XI 1965

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