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TITLE: RAREFACTION VELOCITIES IN SHOCKED LEAD

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RAREFACTION VELOCITIES IN SHOCKED LEAD

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By use of the optical analyzer technique, the bulk sound velocity in shocked lead has been measured at nine points along its Hugoniot in the pressure range 54.5 to 380 GPa. The lowest-pressure points exhibit no sign of solid behavior. The bulk sound velocity is essentially linear with respect to density, and the Gruneisen parameter, γ, fails to follow a constant $\rho\gamma$ model. Results are consistent with zero-pressure values.

1. INTRODUCTION

Shock-induced melting of metals allows investigation of liquid metal physical properties over a range of pressure and temperature presently unattainable by static techniques. Of the physical properties currently accessible in shock wave experiments, the sound velocity is particularly important. Melting along the Hugoniot can be directly observed through measurement of a drop in "first arrival" sound wave velocity with increasing pressure as loss of solidity eliminates longitudinal sound waves. In addition, knowledge of the bulk sound velocity, which is measured beyond the melting curve, allows determination of the thermodynamic Gruneisen parameter in the high-pressure, high-temperature liquid phase.

We have studied lead in the liquid regime along the Hugoniot using a two-stage light-gas gun at the Los Alamos National Laboratory. These experiments supplement high-temperature, expanding-wire sound velocity investigations made on lead over the density range from 5 Mg/m^3 to 10 Mg/m^3.[1] Data on fluid tantalum have suggested a linear relationship between bulk velocity and density in both expanded and compressed states.[2,3] In order to extend the test of linearity to other liquid metals, lead is a particularly good candidate because its low melting temperature makes the fluid state easily accessible. In fact, use of a two-stage gun allows exploration of a density range extending to 25 Mg/m^3. Moreover, the Hugoniot of lead is determined from one of the best-characterized data sets for any material. For these reasons, we have extended sound velocity measurements to a pressure of nearly 400 GPa along the Hugoniot, and to a compression that is more than two-fold. All of our experiments were carried out beyond the melting point on the Hugoniot. This allowed us to determine the thermodynamic Gruneisen parameter for lead throughout our experimental pressure range. Thus lead is now one of the most completely characterized liquid metals in terms of high-pressure, high-temperature properties.

2. EXPERIMENTAL TECHNIQUE

Our experiments directly measure the velocity of a rarefaction wave overtaking a shock wave.[4,5] Upon impact, a shock wave propagates

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forward into the sample as another shock wave propagates backward into the thin flyer. This flyer is molded into a polycarbonate cylinder; as the backward-travelling shock wave reaches the flyer-polycarbonate interface, a rarefaction wave is reflected back toward the sample. Because this rarefaction wave propagates through denser, shocked material, it overtakes the forward-travelling shock wave and causes a sudden reduction in pressure and temperature.

Experimental data are taken with the aid of optical fibers. Our sample target is machined such that its non-impact side has four steps; this side is glued into a brass cell filled with bromoform. This liquid chemical analyzer actually experiences the reduction in temperature as the shock front, having propagated into the analyzer, is overtaken. The four different thickness levels of any given sample allow the analyzer to be "removed" from the experiment, as the shock transit time in the analyzer is extrapolated to zero analyzer thickness. Because optical radiation intensity from a black body is proportional to a high power of the temperature, this technique allows a precise measurement of the sound velocity in opaque materials. Precision is limited primarily by the uncertainty in determining transit times; thus for many shots we can determine the sound velocity to within one percent.

The overtake ratio, R, is defined as the ratio of target thickness--at the rarefaction overtaking point--to impactor thickness. We further define

$$R^* = \left(\frac{1+R}{1-R}\right), \qquad (1)$$

which is related to the rarefaction velocity, c, shock velocity, u_s, and relative density, ρ/ρ_0, by

$$R^* = \left(\frac{\rho}{\rho_0}\right)\frac{c}{u_s} \quad . \qquad (2)$$

For different flyer and target materials, as was the case in our experiments on lead, the overtake ratio R_T for the target (the sample) may be calculated from the observed, "experimental," overtake ratio:

$$R_{exp} = D_{ovt}/D_F = (u_{s_T}/u_{s_F})(R_T+1)[R_F/(R_F+1)] \quad (3)$$

Here, D_{ovt} is the "overtake distance," which is equal to $u_{s_T}\Delta t$, where Δt is the measured overtake time. Also, D_F is the flyer thickness. Subscripts "T" and "F" refer to the target and flyer, respectively. It is evident that flyers with known Hugoniot relations and overtake ratios must be used. Fortunately, these properties have been measured over a wide pressure range for aluminum, iron, and tantalum, thus allowing these three materials to be used as flyers in rarefaction velocity experiments. Because of the wide shock impedance range represented by these three flyer types, we can study new sample materials over a wide range of compression.

The thermodynamic Gruneisen parameter, γ, is defined as $\gamma = V(\partial P/\partial E)_V$, where P is pressure, E is internal energy, and V is specific volume, $1/\rho$. A rigorous thermodynamic argument[6] can be used to obtain γ as

$$\gamma = V\frac{\left(\frac{\partial P}{\partial V}\right)_S - \left(\frac{\partial P}{\partial V}\right)_H}{\left(\frac{\partial E}{\partial V}\right)_S - \left(\frac{\partial E}{\partial V}\right)_H} = 2\,\frac{B_S - B_H}{P - \eta(V_0/V)B_H} \qquad (4)$$

Here, $\eta = 1 - V/V_0 = u_p/u_s$ (u_p is particle velocity), B_s is the adiabatic bulk modulus, and $B_H = -(\partial P/\partial \ln V)_H$ is the bulk modulus along the Hugoniot curve. The subscripts on the partial derivatives refer to evaluation along the Hugoniot (H) or isentrope (S). Knowledge of the bulk sound velocity, c_B, determines B_S as

$$B_S = -\left(\frac{\partial P}{\partial \ln V}\right)_S = \rho c_B^2 \quad , \qquad (5)$$

while B_H is given by

$$B_H = \rho_0 (V/V_0) u_s^2 \ (1+A)/(1-A) \tag{6}$$

with

$$A = ns + 2qn^2 u_s \tag{7}$$

Equation (6) assumes the most general useful form of the Hugoniot relation:

$$u_s = c_0 + su_p + qu_p^2 \tag{8}$$

The form of the Hugoniot relation is discussed further in the next section.

3. EXPERIMENTAL RESULTS

A typical shot record is shown in Fig. 1.

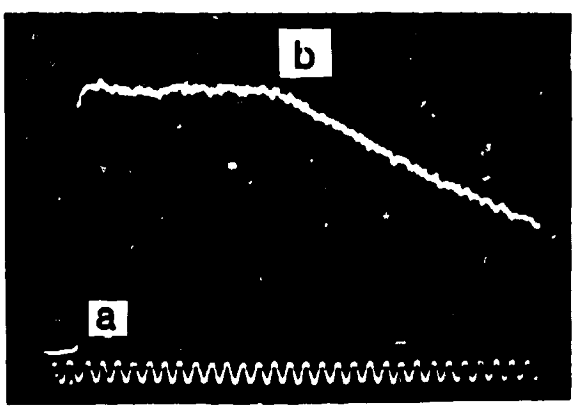

FIGURE 1
A typical shot record for lead. Time increases to the right, voltage (i.e., light intensity) upwards. Time mark adjacent crests are 10 ns apart. a) Shock rise. b) Rarefaction overtake break.

Evident is the sharp rise in light intensity as the shock wave enters the analyzer, the steady output as the shock continues to propagate through the analyzer, and the sharp change in slope (the "break") as the rarefaction wave overtakes the shock wave. This record is one of eight recorded for a completely successful shot; each of four target "steps" is observed through two optical fibers.

The best fit through 72 lead Hugoniot points measured at the Los Alamos National Laboratory yields the relation $u_s = 2.051 + 1.460 u_p$. However, these data extend to a density of 20.7 Mg/m^3, while two of our experimental shots attained greater density. The quadratic relation, $u_s = 2.004 + 1.571 \ u_p - 3.3 \times 10^{-2} \ u_p^2$, determined by Al'tshuler et al.,[7] takes into account both the American data and several Hugoniot points representing substantially higher pressure than that obtainable with a two-stage gun. These two relations agree to within one percent for the range of pressure represented by all but our two highest pressure shots. We believe that this quadratic Hugoniot fit is the best published u_s-u_p relation for lead, and have used it in our analysis. However, new Hugoniot data in the multi-megabar range would provide a more uniform data sampling density for lead.

Our results for sound velocity as a function of density are given in Fig. 2.

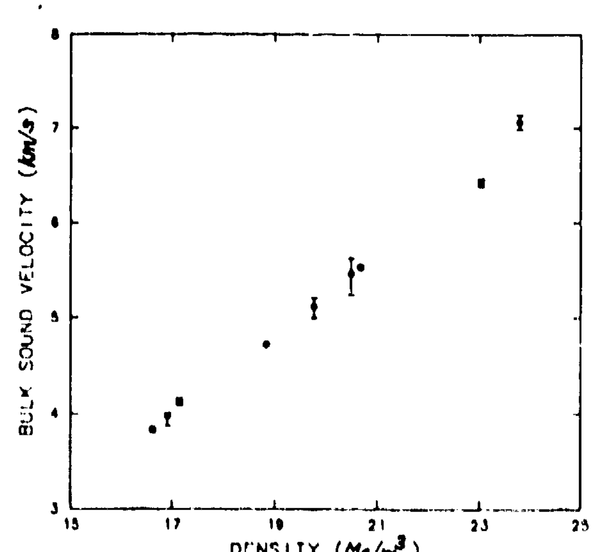

FIGURE 2
Bulk sound velocity as a function of density for lead. These data are consistent with the accepted zero-pressure value of 1.9 km/s.

The lowest-pressure points show no indication of a drop from longitudinal to bulk sound velocity, hence we conclude that all of our data lie beyond the solidus point on the Hugoniot. This is consistent with published results on the melting of lead under shock loading.[8] The data in Fig. 2 span a pressure range of 54.5 to 380 GPa. Our experiments indicate that for lead bulk sound velocity is, to a first approximation, linear with respect to density over a wide compression range. The deviation of our highest-pressure point may be largely due to uncertainty in the Hugoniot relation in this region.

The density dependence of the Gruneisen parameter is plotted in Fig. 3.

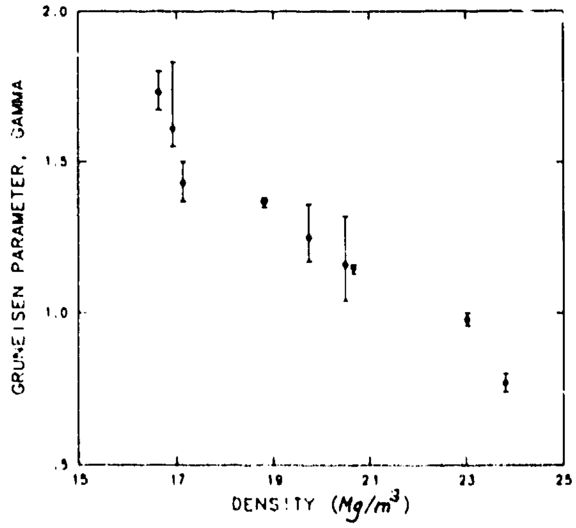

FIGURE 3
Grüneisen parameter as a function of density for lead. These data are consistent with the accepted zero-pressure value of 2.8.

The error bars take into account all experimental uncertainties except uncertainty in lead Hugoniot parameterization. Whereas the sound velocity may additionally vary by 0% to 2.5%, depending on Hugoniot parameterization, the Gruneisen parameter can vary by as much as 10% in our range of data.

Our results indicate that the constant $\rho\gamma$ model, which works as a first-order approximation for other metals,[3] does not hold as well for lead. The variation of $\rho\gamma$ is at least 15% over our span of data.

4. CONCLUSIONS

We have measured the bulk sound velocity in shocked lead at nine points along its Hugoniot in the density range 16.6 to 23.8 Mg/m^3. These data supplement isobaric expansion data on lead, and support the observation that sound velocity varies linearly with density in liquid lead over a very wide density range. However, the simple constant $\rho\gamma$ model is not accurate for liquid lead along its Hugoniot.

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