Analysis of temperature measurements at lead(Pb) / transparent window interface under shock compression

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Abstract. In this paper, we show that if the temperature $T_A$ obtained by a pyrometric measurement on a shock-heated material can be reached with a good precision (~5%), its transformation into a useful temperature $T_T$ to constrain an equation of state is not straightforward. The effects of interface, in particular the adaptation of impedance, can create a difference between $T_A$ and $T_T$ of more than 10%. This impedance correction depends on the shock adiabat of the glue, not known for thin layers of few µm but also of the equation of state of the material and of its lines of phase transition.

1. Introduction
To accurately reproduce temperature for a given P-$\rho$ state is difficult for an equation of state (EOS). Indeed if, Hugoniot data, P-$\rho$ points obtained at room temperature by diamond anvil cell (DAC) and considering the thermodynamics relations, an evaluation of the temperature can be done, this remains only an estimation which depends on the model of equation of state and requires precise data. To specify temperature, additional data are needed. For example, knowledge of the phase diagram and transition pressures under shock can impose strong additional constraints. These data can be obtained by DAC [1] or using an optical pyrometer for temperature measurements on shock-heated material [2]. It is on this latter type of experience that we will focus.

After recalling the general principle of this type of experiment, we will develop the various sources of uncertainties that may occur to extract the temperature of the sample. Finally, we will discuss the differences obtained between a theoretical EOS and various temperature measurements of lead under shock compression.

2. Principle of temperature measurements of lead under shock compression
The principle of temperature measurements is to collect by an optical pyrometer the radiance emitted from a shocked sample (S) (figure 1) (for a gun shot, an impactor (I) create a shock in a transmitter (T) which transmits it to (S)). In our experiments, the radiance L is measured through a window (W, in LiF, sapphire, etc.) which is glued onto (S). The glue (G) then acts as an additional window. A filter transmittance $\tau^F(\lambda)$ permits to select the wavelengths of each detector.

However, converting the radiance into temperature representative of the EOS of (S) is not straightforward and different sources of errors may occur (see figure 1). These can be separated into four main sources of uncertainty:
(1) the transformation by the detectors of the radiance emitted by the sample into voltage \( V(t) \) requires calibration before shot ((a) in figure 1). This calibration is performed for each detector using a blackbody temperature \( T_{BB} \) which connects, via a constant \( \alpha \), the voltage to the radiance \( L : \alpha V = L \).

(2) the time average of \( V(t) \) results in an average radiance \( \overline{L} \) (figure 1(b)) and an average black body temperature \( \overline{T} \) (figure 1(c)). Additional photons can disrupt the calculation of \( \overline{L} \). Among the interference phenomena, that may be mentioned the emissivity and the absorption of the sapphire window or the triboluminescence of the LiF window.

(3) the choice of the effective emissivity \( \varepsilon \) of the surface of the sample seen by the detector is then used to obtain an apparent temperature \( \overline{T}_\alpha \) (figure 1(d)). This choice depends on the emissivity \( \varepsilon^M \) of the sample but also of its surface state as well as of the transmission of glue and window \( \varepsilon'(\lambda) \) which are added after calibration.

(4) If \( \overline{T}_d \) is the temperature of the experiment, it is still not the “real” temperature of the sample \( \overline{T} \). \( \overline{T}_d \) is the only useful temperature to constrain directly the modeling the equation of state of material and different corrections are to be applied to \( \overline{T}_d \): interface corrections and elasto-plastic heating (figure 1(e)).

At these sources of uncertainties in the temperature measurement itself, one could add uncertainty on the knowledge of the shock adiabat (figure 1(f)). These connect the impact/interface velocity to pressure and to density reached by the sample at the surface. In general, impactors and transmitters are standard materials and are well-characterized. It is the same for windows. Lead also has a well-defined shock adiabat. If only the impact velocity \( u^I \) is measured an uncertainty of 2% to 3% in the determination of the pressure at the surface of the sample \( P^S \) is typically reached. If the interface velocity \( u^S \) is also measured, an uncertainty less than 1% in the determination in pressure at the interface can be achieved.

Figure 1. Principle of measurements by an optical pyrometer under shock. \( c_1 \) and \( c_2 \) are the optical constants.
3. Source of uncertainties

Concerning point (1), if we consider that the radiance uncertainty is \( \Delta L = \delta L / L \), the uncertainty of the temperature \( \Delta T = \delta T / T \) can be approximated as \( \approx \ln(1 + \Delta L) / \ln(e_1 \delta L / L^2) \) or \( \Delta T \approx \Delta L \lambda T / c_2 \) (\( \delta \lambda \) is the width of the filter assumed square). For this type of experiment, \( \lambda T / c_2 \) is close to 0.1 and can be reduced by the use of the shortest wavelength. Thus, a noisy or poor calibration signal does influence only weakly the determination of the temperature. Accuracy of the order of a few percent on the temperature is typically achieved with a correct acquisition chain.

For point (2) if the peculiar emissivity and absorption of the sapphire window can significantly change the brightness, the extrapolation of \( L \) at the shock breakout provides the correct flow emitted from the surface \([2,3]\). Similarly, the effects of triboluminescence related to a LiF window conduct to a peak having a low temporal extension and the origin of these peaks (broken chemical bonds) make them dependent on the wavelength. If the acquisition time of \( V(t) \) is sufficient and different wavelengths are used, their effects may be eliminated when calculating \( L \). In addition, technical solutions exist to eliminate these effects (increased diameter of the LiF window to delay the arrival of the waves on the edges for example). These two points ((1) and (2)) generate an uncertainty of 1-3% on the measurement of temperature and this thanks to \( \Delta T \approx 0.1 \Delta L \).

Point (3) is more problematic. The uncertainty in temperature due to the emissivity is \( \Delta T \approx (\delta e / e) \lambda T / c_2 \). If the emissivity of the metal surface under impact is not known, \( e \) is generally chosen between 0.1 and 1, resulting in a \( \Delta T \) of about 5-6%. However, calculations taking into account the surface state, optical indexes and absorption of the glue, the use of different wavelengths or of an integrating sphere measurement allow to restrict this choice. In this case, the uncertainty on the apparent temperature \( T_{app} \) ((1)-(2)-(3) points) is generally less than 5%.

The conversion of \( T_{app} \) in true \( T_{metal} \) is more difficult (item (4)). An estimate of the elastic-plastic heating can be obtained by difference using a hydrodynamic code calculation. In the case of lead, elastic-plastic heating is almost nil (< 0.1%).

Due to the presence of glue, good thermal insulator, cooling by thermal conduction is low (if only this effect occurs at the interface \( T_{app} \approx T_{glue} \) [4]. The effects of the metal/glue/window impedance mismatch are more difficult to estimate. Indeed, the real thermodynamic path is not a shock followed by a direct release isentrope on the window. The shock passes through the sample (S) which is then in a state \( I \). Then (S) will relax on the thin layer of glue (G) up to state 2 (figure 2).

![Figure 2. Schematic representation of the impedance matching.](image)

The glue then undergoes a shock wave that is reflected on the window (state 3) before being reflected back to the sample (state 4), etc. and this until the steady state \( F \) is reached, this in just a few ns. The path followed by the surface is a shock at the state \( I \)-release to state 2, followed by shocks and re-shocks (states 4-6-...) and the equilibrium to state \( F \). It should be noted that the thermodynamic path \( I-2-4-...F \) only changes slightly the interface velocity \( u^i \) relative to a direct path \( I-F \) and this.
variation is indistinguishable by velocity measurements, except if the properties of the phase in the state 2 and the properties of the phase in the state F are strongly different.

Then the correction is dependent on the glue shock adiabat but also on the equation of state of the metal. When relaxation and the equilibrium state are in the same phase (case I-F on the figure 2), the correction is mainly due to shock adiabat of the glue and to the shock between states 2 and 4. If release occurs on a line of phase change, it is it which will guide the correction. Thus, for the I state, shock and release are in phase 2, but the impedance mismatch leads to the state F which is located on the line of phase change. If the shock is on I, the path remains on the mixing line and no correction should be made to the temperature $T_A$.

4. Comparison between measurements and modeling

The equation of state of lead [5] is modeled by two phases (solid-liquid) using the construction tool Panda [6]. This EOS is constrained to reproduce dynamic adiabat, the room temperature isotherm in h.c.p. phase above $\sim 15$ GPa ($\rho_0 = 11.420$ g.cm$^{-3}$, $K_0 = 421$ GPa et $K'_0 = 5.63$ with a Rydberg-Vinet EOS formulation) [7] and the temperature of melting for the pressure of melting under shock ($P_{\text{shock}} \sim 50$ GPa) [8]. The theoretical room pressure temperature density is $\rho_0 = 11.350$ g.cm$^{-3}$. The obtained theoretical melting curve (dashed line in figure 3) is, by construction, in good agreement with the measurements [1,2] (circles and full line on figure 3).

In figure 3, we also added temperatures $T_A$ (without interface corrections) obtained by pyrometric measurements under shock for which the thermodynamic state I is that of a solid phase (empty diamonds and squares) [3,9]. The corresponding theoretical temperatures $T_T$ (shock followed by a direct release on the window) are reproduced by the full diamonds and squares. We have also reproduced the state 2 obtained by considering that the glue shock adiabat is the same of that of an epoxy [10] (for each triangle in the figure 3, the number corresponds to the pressure of the metal at the state I, the coordinates P and T are those reached by the metal at the state 2).

We immediately notice that $T_A$ measured is 10% to 15% greater than to calculated $T_T$. This difference, larger than the expected uncertainty for $T_A$ can obviously not be due to a fault in the modeling. An increase in temperature of several percent implies, to agree on the adiabat, to degrade the $T = 300$ K isotherm by decreasing $K'_0$ beyond the DAC uncertainty ($K'_0 \sim 4.5$). Moreover, if the increase in the coefficient of Grüneisen induced by such modeling allows an increase in temperature on main Hugoniot (and therefore for the sapphire points), the LiF points are not corrected (in this case, the temperature decreases more along release isentrope). The interference phenomena could not more explain a systematic variation of more $\sim 50\%$ on the radiance (see above).

The interface effects arising from the glue “window” can largely explain the discrepancy. The use of a thermal insulator is inevitable and the glue is perfectly suited (heat conduction in window is close to a metal and the absence of insulator would result in a temperature $T_A$ of the order of $(T_T(S) + T_T(W))/2$). The counterpart is the impedance mismatch effect.

Thus, for points which have a shock pressure greater than $\sim 35$ GPa and which are initialized solid in I, multiple shocks take place close to the expected melting curve. If the melting curve is reached, the state F is located on the melting curve (case I-F in figure 2 and the five higher pressures represented by empty diamond in figure 3). In the case where the state I is on the melting curve, F is also on and none correction is necessary (case I-F in figure 2 and the Partouche’s data in figure 3).

For lower pressure ($P_{\text{shock}} \leq 35$ GPa) (LiF points and sapphire point at 30 GPa), the interface corrections are mainly dependent on f.c.c. to h.c.p. phase change and shock adiabat of the glue (case of I1-F1 in figure 2). The phase transition is almost vertical; phase change should little modify temperature. Considering the epoxy adiabat, succession of shocks result in an increase of $T_T$ of $\sim 2\%$ for these points. If we consider the glue adiabat of an epoxy as legitimate for thick layers, this is not
obvious for thin layers (20 ± 10 µm). A decrease of factor 2 on b in the $u_s = a + bu_p$ relation would increase $\overline{T_T}$ of ~ 5% for these points.

![Figure 3. Phases diagram of lead [1,11] (color online). Temperature measurements $\overline{T_A}$ are in empty symbols, calculated temperatures $\overline{T_T}$ are in full symbols. The thermodynamic path for $P_{\text{shock}} = 35$ GPa is represented by the I-2-4-6-F points (case $F^2-F^2$ in figure 2).](image)

To conclude, if pyrometric device under shock is a perfect tool for determining the temperature of a material, especially if we reach a phase boundaries (as is the case in experiments [2] and sapphire data for $P_{\text{shock}} \geq 35$ GPa), it is annoying to see that unfamiliarity with the interface effects can involve a change in the temperature of the same order of magnitude as the expected uncertainty on $\overline{T_A}$. Experimental studies are provided for determining the shock adiabatic with a thin layer of glue and thus enable to specify the data in pure phase.

References
[1] Dewaele A, Mezouar M, Guignot N and Loubeyre P 2007 Phys. Rev. B 76 144106
[2] Partouche-Sebban D et al 2005 J. Appl. Phys. 97 043521
[3] Pélissier J-L Private communication.
[4] Urtiew P A and Grover R 1974 J. Appl. Phys. 45 140-145; Grover R and Urtiew P A 1974 J. Appl. Phys. 45 146-152
[5] Legrand P Private communication
[6] Kerley G I 1991 Sandia Report Sand88-22-91-UC-405
[7] Dewaele A Private communication
[8] Benier H and Lalle P Private communication
[9] Robert G, Bénier J and Gillot F Private communication
[10] Lyon S P and Johnson J D The Los Alamos National Laboratory equation of state database 1992 Los Alamos National Laboratory Tech. Rep. LA-UR-92-3407 (see SESAME-7601); Pélissier
J-L Private communication

[11] Kuznetsov A, Dmitriev V, Dubrovinsky L, Prakapenka V and Weber H-P 2002 Solid State Comm. 122 125-127