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HUGONIOT MEASUREMENTS AT LOW PRESSURES IN TIN USING 800 MeV PROTON RADIOGRAPHY

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Abstract. A 2cm long 8 mm diameter cylindrical tin target has been shocked to a pressure in the region of the $\beta \rightarrow \gamma$ phase change using a small, low density PETN charge mounted on the opposite side of a stainless steel diaphragm. The density jump and shock velocity were measured radiographically as the shock wave moved though the sample and the pressure dropped, using the proton radiography facility at LANL. This provided a quasi-continuous record of the equations of state along the Hugoniot for the P1 wave from a shock velocity of 3.25 km/sec down to near the sound speed. Edge release effects were removed from the data using tomographic techniques. The data show evidence for a phase transition that extends over a broad pressure range. The data and analysis will be presented.

Keywords: proton radiography, equation of state, tin.
PACS: 47.40.-x, 47.40.Nm, 29.27.Eg, 29.40.Wk, 47.79.Pw

INTRO

During the 1950's and 60s new techniques were invented for measuring the equation of state of materials under high pressure. These involved two fundamentally different techniques - the Bridgman press and shock driven experiments. In the former, materials are compressed using a high pressure diamond cell anvil, and in the latter pressure is created using shock techniques. Diamond anvil cells allow very high pressures to be obtained, but diagnostics on small compressed samples are difficult. Shock driven experiments allow precision measurements of a set of points in the EOS space that lie on the Hugoniot. Comparisons between these two methods of measurement rely on the assumption that the shocked samples reach thermal equilibrium. In some cases involving phase changes this is known not to be the case. Understanding the dynamics of materials undergoing shock induced phase changes can only be obtained from shock driven experiments.

Most shock driven experiments have been studied using surface diagnostics. Exceptions included several recent experiments using radiographic diagnostics to measure bulk density. In this paper we present data taken on a tin sample that was shocked with a Taylor wave produced by a small high explosive charge of PETN. Densities were measured using 800 MeV protons provided by the LANSCE accelerator in Los Alamos at the proton radiographic facility [1]. The phase transformation, P1, wave was inferred from the radiographic data and compared to tabulated values to determine the Hugoniot for tin.

EXPERIMENTAL PROCEDURE

An empirical model (Eq. 1) for the transmission of energetic protons through material [2] allows areal densities to be obtained from proton radiography.

$$t_{corrected} = e^{-\frac{\rho}{\lambda_j}} \frac{1 - e^{-k\frac{Xj}{\rho}}}{1 - e^{-\frac{k}{X_{fixed}}}} \qquad (1)$$

$$k = \frac{1}{2}\left(\frac{p\beta\theta_c}{MS_{factor}}\right)^2$$

In the past, carefully designed plate impact powder gun experiments have demonstrated measurements to a precision of better than 1%. Density jumps that agreed with well known Hugoniot points on copper and 6061-T6 Aluminum alloy were measured to better than 0.5% [4].

In this paper we describe a Taylor wave driven experiment using tin. In Fig 1, a cartoon is shown of the sample setup.

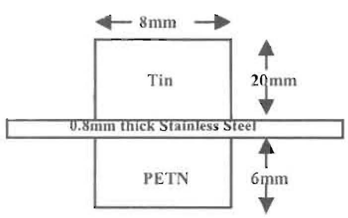

FIGURE 1. Sample setup for Taylor wave-driven Proton Radiography dynamic experiment.

One of the important and unique features of proton radiography is its ability to record multiple high-resolution images (a movie) of rapidly evolving dynamic phenomena down to the 100 ns inter-frame time scale.

In this experiment, dynamic radiographs were taken at 18 different times spaced by 300 ns across the development of the experiment. Transmission was calculated from the radiographs by dividing them by beam pictures taken after the dynamic experiment. The position scale was calibrated by radiographing a fiducial plate that consisted of 3mm long tungsten rods precisely located on a polycarbonate plate. Fits to the location of the fiducial markers gave root mean squared (rms) errors less than 20 um. Systematic errors due to the uncertainty in the magnification of the optics system used to image the fiducial plate onto the object plate are estimated to be as much as several percent. Although this is the limiting error of the current experiment it can be reduced to a negligible level in future experiments by direct measurement.

RESULTS AND DISCUSSION

A composite picture of the 18 radiographs is presented in Fig 2. The radial release after the passage of the shock is apparent in these pictures.

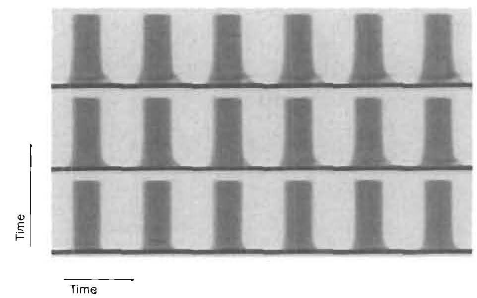

FIGURE 2. Transmission as a function of time. Time increases from left to right in 300 ns steps and from bottom to top in 1800 ns steps.

When the dynamic radiographs are divided by the static radiographs, the shock becomes apparent. This is shown in Fig 3.

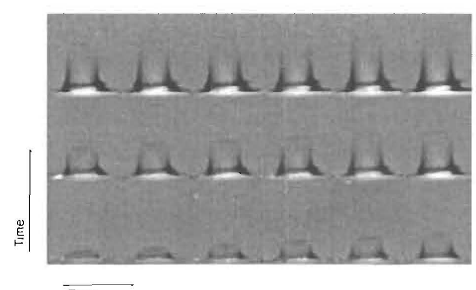

FIGURE 3. Ratio of the dynamic radiographs to the static ragiographs. The times presented are the same as described in **Error! Reference source not found.**.

In order to obtain quantitative density jump and shock locations from the data we have 1) inverted the static and dynamic radiographs using Eq. 1 to obtain areal densities; 2) Calculated volume densities from the areal densities by inverting the following equation:

$$\rho_A(r_i) = \sum \rho_V(r_j)P_{i,j} \qquad (2)$$

with the addition of a small regularization term to the linear fit. Here $\rho_A(r_i)$ is the areal density for the ith shell, $\rho_V(r_j)$ is the volume density for the jth shell and $P_{i,j}$ is the path length through the shell. This inversion is performed independently for each row of the image. 3) The resulting volume density is set to zero for r > rmax, and 4) a trimmed areal density, $\rho_{AT}(r_i)$ is calculated as

$$\rho_{AT}(r_i) = \sum_0^{r_{\max}} \rho_V(r_j)P_{i,j} \qquad (3)$$

This quantity is the areal density in a core of the shocked sample. Finally 5), a ratio of the static and dynamic trimmed area density is calculated. The results showing the time development of the shock in the center of the sample are presented in Fig. 4.

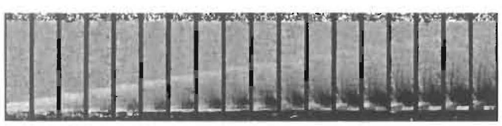

FIGURE 4. Density ratio as a function of position and time of 18 radiographs with 300 ns inter-frame time.

The extracted shock locations and density jumps are plotted vs. time shown in Fig 5. A polynomial was fitted to the shock locations and its derivative was used to find the shock velocity as a function of time. Although this procedure places constraints on the data that may be non physical-noise in the data prevented direct extraction of the velocities. When these data are plotted with respect to the existing Marsh Compendium data [5], shown in Fig. 6, they are suggestive of the observation of a phase boundary along the Hugoniot. In future experiments we hope to obtain better statistical precision in the edge determination that will allow more precise edge location and less constrained velocity determinations. Direct comparison of the densities behind the shock front may provide important information on the dynamics of the phase transformation and reversion on release.
This will require a comparison with hydrodynamic models.

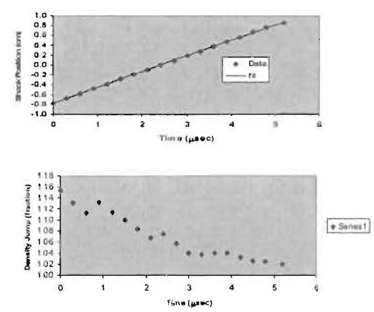

FIGURE 5. Fitted shock position and density jump as a function of time.

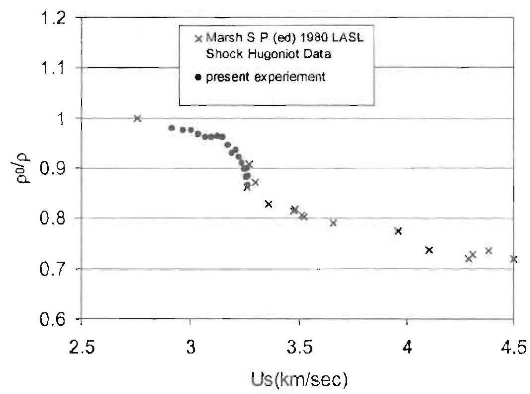

FIGURE 6. Preliminary Hugoniot data from this experiment compared to the Marsh Compendium data.

CONCLUSIONS

New direct measurements of the motion of a Taylor wave driven shock through a tin sample using proton radiography have been presented. These have been analyzed using a novel method that provides approximately one-dimensional information in the vicinity of the shock wave.

These measurements suggest proton radiography may provide a new method for obtain data on the kinetics of shock induced phase transformations.

ACKNOWLEDGEMENTS

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