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Title: Investigation of Surface Phenomena in Shocked Tin in Converging Geometry

Author(s):
Rousculp, Christopher L.
Oro, David Michael
Margolin, Len G.
Griego, Jeffrey Randall
Reinovsky, Robert Emil
Turchi, Peter John

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Investigation of Surface Phenomena in Shocked Tin in Converging Geometry

C. L. Rousculp, D. M. Oro, L. G. Margolin, J. R. Griego, R. E. Reinovsky, P. J. Turchi - 17 February 2015

Introduction

There is great interest in the behavior of the free surface of tin under shock loading. While it is known that meso-scale surface imperfections can seed the Richtmyer-Meshkov Instability (RMI) for a surface that is melted on release, much less is known about a tin surface that is solid, but plastically deforming. Here material properties such as shear and yield strength come into play especially in converging geometry.

Previous experiments have been driven by direct contact HE. Usually a thin, flat target coupon is fielded with various single-mode, sinusoidal, machined, profiles on the free surface. The free surface is adjacent to either vacuum or an inert receiver gas. Most of these previous driver/target configurations have been nominal planer geometry. With modern HE it has been straightforward to shock tin into melt on release. However it has been challenging to achieve a low enough pressure for solid state on release.

Here we propose to extend the existing base of knowledge to include the behavior of the free surface of tin in cylindrical converging geometry. By shock loading a cylindrical tin shell with a magnetically driven cylindrical liner impactor, the free surface evolution can be diagnosed with proton radiography. With the PHELIX capacitor bank, the drive can easily be varied to span the pressure range to achieve solid, mixed, and liquid states on release. A conceptual cylindrical liner and target is shown in Figure 1.

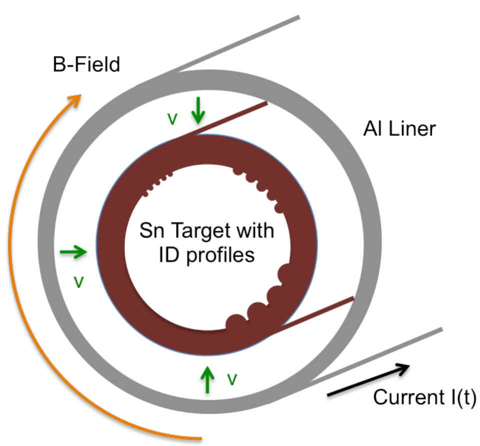

Figure 1. Conceptual cylindrical and target. The target has thee different single-mode flute profiles on the inner surface.

Motivation

Current computational modeling paradigms of ejecta[1] are broken down into production, transport, and evolution. The production model is based on characteristic surface roughness and material phase. When a fluid, non-smooth surface is subject to shock, the RMI produces spikes of material that can be ejected from the surface. This model has been verified and quantified in an extensive series of experiments where single mode initial surface perturbations were subject to HE shock loading and melt on release[2,3]. Proton radiography imaged nonlinear amplitude growth and piezo pins measured total ejected mass as a function of time. However, one shortcoming of these HE driven experiments is that the drive is fixed and it is difficult to shock a tin sample such that it is solid on release. Thus a variable drive method that could span the range of pressures for release into solid, mixed, or fluid state would be highly valuable.

Recent theoretical work on the EOS of tin has modified both the Hugoniot and the isentropes for release into various states in tabular data. The new multiphase EOS for tin, SESAME 2161, includes the beta and gamma solid phases as well as a liquid phase. It predicts a lower pressure boundary for release to pure solid (~20 GPa) and a higher pressure boundary for release to pure liquid (~35 GPa) than the existing SESAME 2160 table. Seen in Figure 2, is a phase space comparison of the two tables[4]. Experimentally, the new table requires a much broader range of accessible pressure drive to validate.

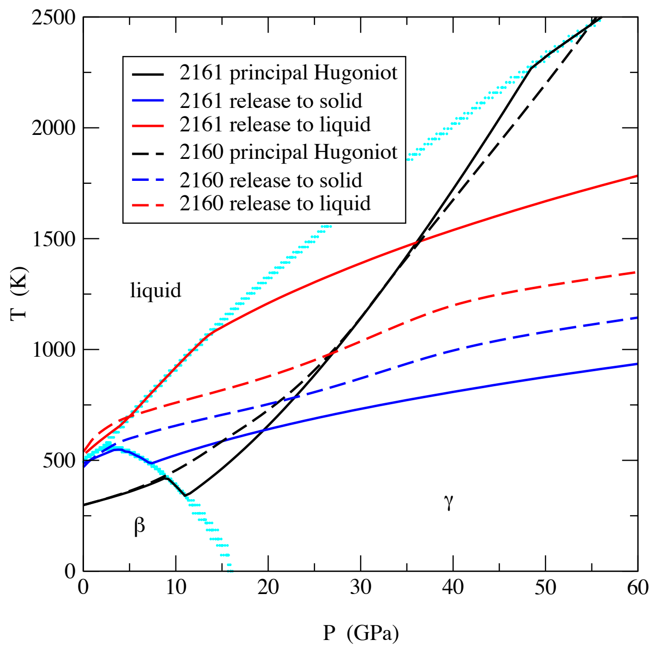

Figure 2. Phase diagram comparing multiphase SESAME 2161 with 2160.

The main technique for the study of RMI growth and validation of models has been single-mode sinusoidal profile of a planer tin surface. However, if a similar profile is imposed on the inside of a cylinder, it is not as clear what the mechanism for amplitude growth might be when the cylinder is driven radially inward. On the one hand, for a fluid surface the RMI will invert the peaks and troughs and cause spike and bubble formation. However, if the surface is neither shocked nor fluid it may be subject to a Bell-Plesset type instability. A general theory for the evolution of a single-mode sinusoidal surface on a cylinder has been proposed[5] in which amplitude grows as

$$A(t) \approx \frac{\sqrt{4R_0 vt}}{N}$$

Here, R_0 is the initial cylinder radius, v is the surface's radial velocity, and N is the number of oscillations around the cylinder, such that $N = 2\pi R_0/\lambda$, where λ is the azimuthal wavelength. Also, it is assumed that and $NA(0)/R_0 << 1$. This theory is based on conservation of surface area and general enough to include compressible fluids and solids. Also, the theory is general enough that the velocity may be considered a function of time.

Previous Work

It should be noted that previous work has been conducted on shock loading with magnetically driven liners onto cylindrical shells with the Pegasus pulsed power machine[6]. There, four frames of axial flash X-ray clearly imaged the growth of single-mode surface profile on a cylindrical aluminum target under shock loading ranging from 14 to 50 GPa. More recently, planer, HE driven experiments with copper samples and varying single-mode profiles have investigated the effect of yield strength upon shock release to solid[3,7].

Experimental Method and Proposed Work

PHELIX is a 300 kJ capacitor bank located at the LANL LANSCE pRad facility. It is capable of delivering a 4 MA, 10 us current pulse to a low inductance cylindrical load. A picture of PHELIX at pRad is shown in Figure 3.

Figure 3. PHELIX at pRad.

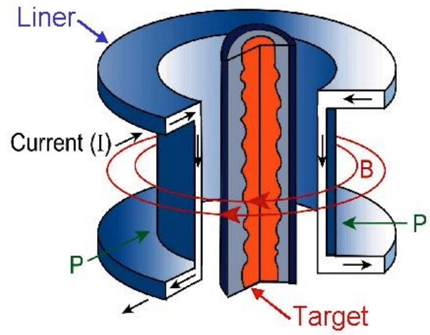

Figure 4. Schematic of a magnetically driven, liner-on-target experiment.

A general, magnetically driven, cylindrical liner-on-target, shock experiment is shown in Figure 4. An axial directed current, *I,* produces a azimuthal directed magnetic field, *B.* Lorentz force subjects the liner to a radially inward, driving pressure,

$$P = \frac{\mu_0 I^2}{8\pi^2 R^2}$$

Here, *R* is the cylinder radius. Thus, there are two ways to vary the liner impact velocity and shock pressure in a target. First, the initial voltage on the capacitor bank (which is directly proportional to the current) can be varied. Second, the initial liner radius can be varied. A precise method for experiment design is to first find liner dimensions and initial voltage that can achieve a high enough impact velocity for release to pure fluid for a given size target. For subsequent experiments that release to a mixed state or pure solid, simply increasing the target size can reduce the pressure. (Alternatively, the geometry can be kept constant and the charge voltage and therefore the peak current can be reduced.)

Initial calculations with the 1D Lagrangian MHD code, Raven[8], indicate that a PHELIX driven liner experiment can produce the required range of shock pressures in a tin target (20 > P > 35 GPa). Figure 5 shows the results of an Al liner (R_0 = 1.1 cm, δr = 0.1 cm) impacting a tin target (R_0 = 0.5 cm, δr = 0.1 cm). The liner achieves a velocity at impact of 3.6 km/s. By plotting the temperature vs pressure for various cells in the target it is apparent that this configuration is sufficient (P > 35 GPa) to achieve the predicted on release to a pure fluid state.

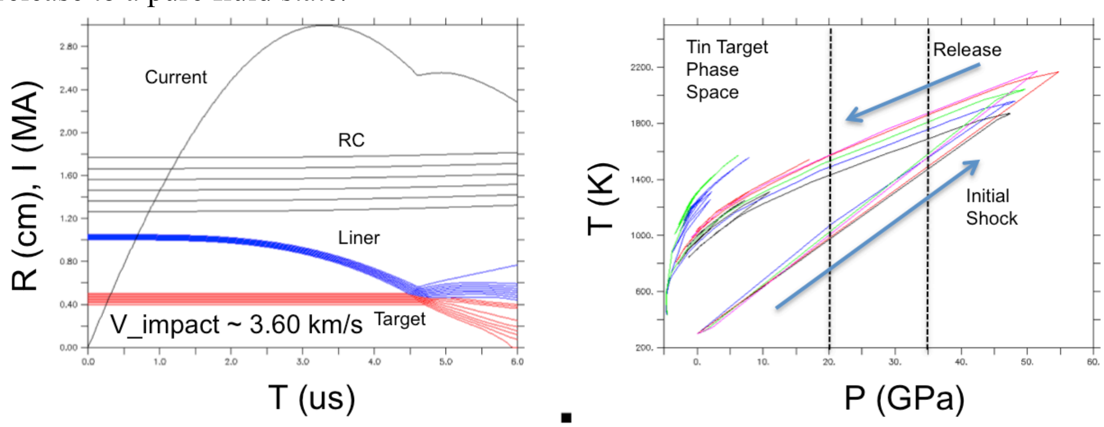

Figure 5. (Left) Radius vs time plot of liner, target, RC and load current. (Right) Phase space plot of selected Lagrangian cells in the tin target. All are above the 35 GPa threshold for release to pure fluid.

By increasing the target size (R_0 = 0.9 cm, δr = 0.1 cm), with identical liner and initial voltage, the impact velocity is decreased to ~ 1.26 km/s. This is shown on the left in Figure 6. This facilitates a lower shock pressure (P < 20 GPa) in the target as show on the right in Figure 6.

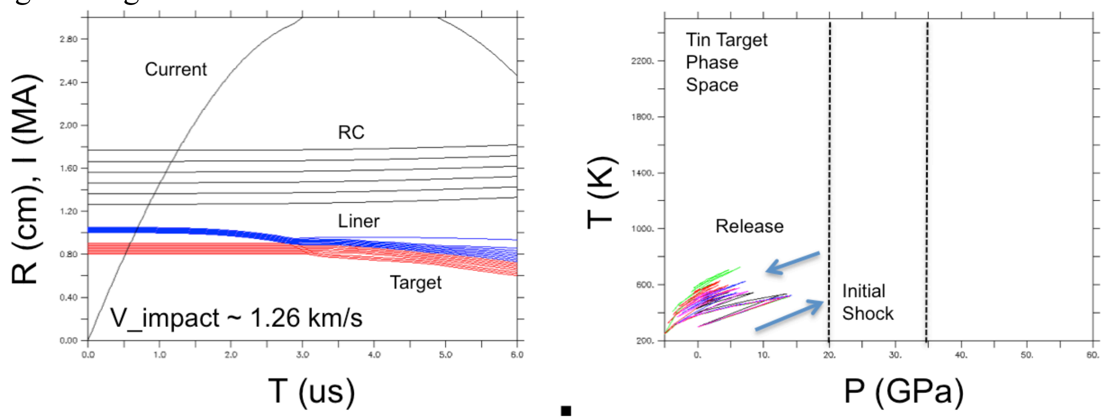

Figure 6. (Left) Radius and current vs time of a liner, target, and RC. (Right) Phase space of selected Lagrangian cells in the tin target. All are below the 20 GPa threshold for release to solid.

The next design consideration is the single mode perturbation amplitudes and wavelengths. As depicted in Figure 1, if the smaller target ID (perimeter = 2.51 cm) is divided into quadrants, then three can have perturbations and one can have a smooth surface as a reference. The preferred choice would be identical to the planer experiments (λ = 550 μm, with 10 < A(0) < 200 μm) for direct comparison. A shortcoming of the cylindrical targets is that spikes could only evolve as far as the initial radius of before colliding with each other on axis. However, this should be far enough to reach the nonlinear regime.

Proton radiography considerations include the areal density, choice of magnification system, and radiograph timing. All calculations have been made assuming a 2.8 cm long target cylinder. This gives a static areal density of the target cylinder of 19.7 g/cm^2. It should be noted that the fielded experiment will include Al end caps of ~1 cm thickness. This gives a total initial areal density of ~25 g/cm^2. As for magnification systems, the X7 (15 mm FOV) would be ideal for the smaller 0.5 cm radius target. It would be able to image the whole target. However, only a portion of the larger 0.9 cm radius target would be captured with this system. Therefore some refinement of the design will be necessary. Finally, the first radiograph would be timed just before liner impact and the final image would be as the target converges on axis.

The other diagnostics for these experiments include the standard PHELIX suite:

- Optical Faraday rotation for measuring load current
- Single frame transverse flash X-radiography
- B-dot probes in the experimental cassette for timing
- Linear Rogowski probes for measuring bank current
- Capacitor bank charge voltage monitor

It has been demonstrated that PHELIX driven experiments can have a turnaround time of two working days. Therefore, it is reasonable to expect two shots within a week of pRad time as long as the LANSCE accelerator has high enough reliability. The objective of the first experiment would be to shock the tin target to pure fluid on release, While the second would attempt to shock to pure solid.

2D calculations with the ASC Flag hydrocode would be performed to predict the flow behavior. A comparison of tin EOS and strength models would be appropriate. This would allow a direct comparison to both the experiments as well as theory of the amplitude growth.

Summary

A method for the study of dynamic surface phenomena in shocked tin in converging geometry has been proposed. The method employs the PHELIX pulsed-power driver to magnetically propel a cylindrical Al liner into a cylindrical Sn target. The range of pressures accessible spans the predicted range of release to pure solid to pure fluid. The target would have single-mode perturbations machined on the inner surface. Proton radiography would image the evolution. Results would be compared to theory and 2D calculation with the ASC Flag hydrocode.

Depending on the outcome of the initial experiments, there are two paths forward with this design. The first would be to bridge the gap in phase space between release to pure solid/fluid and examine intermediate pressures (20 < P <35 GPa) where release to a mixed state is predicted. The second path would be to examine the effect of release into an inert gas where drag and shock interaction take place.

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