Explosively driven two-shockwave tools with applications

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Abstract. We present the development of an explosively driven physics tool to generate two mostly uniaxial shockwaves. The tool is being used to extend single shockwave ejecta models to account for a second shockwave a few microseconds later. We explore techniques to vary the amplitude of both the first and second shockwaves, and we apply the tool experimentally at the Los Alamos National Laboratory Proton Radiography (pRad) facility. The tools have been applied to Sn with perturbations of wavelength $\lambda = 550$ $\mu$m, and various amplitudes that give wavenumber amplitude products of $kh = 8$, where $h$ is the perturbation amplitude, and $k = 2\pi/\lambda$ is the wavenumber. The pRad data suggest the development of a second shock ejecta model based on unstable Richtmyer-Meshkov physics.

1. Introduction
Los Alamos National Laboratory (LANL) has been studying damage processes of shocked materials for several decades. The chief goal is to better understand material failure processes so that hydrodynamics codes can provide a better predictive capability of material failure. Failure modes include spall, cavitation, and other damage processes, including elastic and plastic deformations and the formation of shock induced ejecta.

The shockwaves that load a metal are quite different when caused by a gun versus high explosive (HE). With a gun the shockwaves are “supported,” which means the loading impulse does not decay significantly with time behind the loading stress wave. In contrast “unsupported” HE loaded metals experience a peak stress at loading that decays with time and distance behind the shockwave as lower pressure rarefaction waves overtake it. Of importance is what happens to metals when the two types of shockwaves reach the metal interface, with either a vacuum or pressurized gas. The supported wave will release and reflect back into the metal with an inverse loading pressure rarefraction waves overtake it. It of importance is what happens to metals when the two types of shockwaves reach the metal interface, with either a vacuum or pressurized gas. The supported wave will release and reflect back into the metal with an inverse loading pressure, releasing to zero pressure, but unsupported waves release to zero pressure at the surface but into tension within the bulk – this is true whether vacuum or gas is beyond the metal surface because shockwave pressures are $P_{shk} \sim \mathcal{O}(100)$ kbar, but gasses are $P_{gas} \sim \mathcal{O}(10)$ bar. The damage processes are different for these two loading and release profiles [1, 2].
In our ejecta studies we have mainly studied Sn [3–8] with supported and unsupported shockwaves [6, 7]. Tin is interesting because it has a stable body centered tetragonal (BCT) room temperature solid $\beta$-Sn phase [9], which phase transforms under pressure to a higher density BCT $\gamma$-Sn phase, or with a strong shock it can transform directly to a liquid phase. If it shocks from $\beta$- to $\gamma$-Sn it can release to $\beta$-Sn or a mixed solid-liquid phase. The onset of melt-on-release for $\gamma$-Sn is with a shock-breakout pressure $P_{SB} \approx 19.5$ GPa. If $P_{SB} \approx 33$ GPa the Sn releases to a 100% liquid phase, but for $19.5 \lesssim P_{SB} \lesssim 33$ GPa the Sn releases to the mixed solid-liquid phase. The extremes of $P_{SB} \gtrsim 50$ GPa shocks $\beta$-Sn directly to a liquid that releases to liquid.

In our previous studies we learned that the formation of ejecta mass from shocked metals is linked to: the wavelengths and amplitudes of the surface perturbations; the material phase on release; and, to the shape, profile, and magnitude of the loading impulse [6, 7]. For machined materials the perturbations are usually characterized by linear, two-dimensional (2D) features. While the perturbations may have multiple frequencies, typically one frequency or wavelength is dominant for standard machining practices, such as caused by fly-cut or lathe machining. When the shockwave interacts with the perturbations a 2D sheet of mass is ejected with a mass-velocity distribution. These mass ejections are evidenced as unstable Richtmyer-Meshkov (RM) impulse phenomena [10, 11]. Based on our earlier work we have developed a RM-physics first-shock ejecta model [12].

Following the Sn studies that led to the RM model, we have continued to study other ejecta physics issues, including: ejecta mass size and velocity distributions with Holographic [13] and dynamic Mie scattering techniques; ejecta transport in gasses [14]; and, ejecta phenomena related to multiple shockwave events. With Sn the second-shockwave loading process can occur along different paths. For example, the first shockwave could be with the first shock breakout pressure $P_{SB}^{1} < 19.5$ GPa such that the Sn is solid on shock loading and release. Then the second shock event occurs some time later with the Sn in a relatively elevated thermodynamic state. Additionally, the first shock could leave the Sn released to a mixed solid-liquid state that is subsequently shocked once more. These are the physics that we are studying with HE.

![Figure 1. The two shockwave package design (left), and the CTH [17] mock-up (right). The momentum trapping is seen as two Sn rings around a central Sn disk (right). The HE lens shown to scale is comprised of TNT (Orange) and PBX 9501 (Yellow). The acetal is dark gray, and the anvil is red. The Sn is two colors, and the Ti is in deep blue. All contours are to scale.](image-url)
2. An explosively driven two shockwave physics tool

The development of an explosively driven two-shockwave tool at LANL began in 2006. Recent successes that implement ideas developed by Buttler and Olson reveal an explosively driven two-shockwave tool that allows variation of the first shock stress $P_{SB}^1$, the second shock stress $P_{SB}^2$, and the time interval $\Delta t_{12}$ between the first and second shockwaves. One key design element positions HE in contact with an “anvil” metal that is the source of the second shockwave. Another key design feature includes a composite booster, beyond the anvil, that is comprised of a thin layer of PBX 9501 followed by a lower Chapman-Jouget (C-J) stress explosive, e.g., TNT. The C-J pressure for PBX 9501 is $P_{CJ}(9501) = 34.8 \pm 0.3$ GPa [15], but $P_{CJ}(TNT) \approx 21$ GPa [16].

A typical physics package (see figure 1) encases in acetal plastic a P076 (76 mm diameter) HE lens that drives a 6.35 mm tall PBX 9501 booster. This booster drives a shockwave through the 2 mm Ta anvil into a composite booster that includes 2 mm of PBX 9501 followed by $\approx 5$ mm of TNT. The shockwave leaving the anvil initiates the PBX 9501 that then initiates the TNT. The TNT drives a shockwave into the Ti and Sn target, an assembly of 4 mm of Sn epoxied onto 1.5 mm of Ti. The Ti target support reflects a shockwave back through the HE byproducts toward the anvil that reflects the shockwave back toward the target assembly to cause a subsequent second shockwave to the Sn target. This concept was simulated with CTH [17]. The image to the right of figure 1 shows the CTH generated two-wave 2D simulation geometry to scale.

In CTH, to drive the HE lens we used a Jones-Wilkins-Lee (JWL) EOS for a TNT initiator that reactively [18] detonates the PBX 9501 HE lens component. We conclude that the CTH simulation, based on experimental observations, approximates the desired behavior.

Figure 2 includes one-dimensional (1D) plots from the 2D CTH simulations of the free-surface velocimetry (right), and pressure (left) at $t = 12.5 \mu$s along the central physics package axis. We used a minimum-pressure ($P_{min}$) damage model that allows the Sn to fail when it releases to negative pressures of $P_{min} < -0.15$ GPa. The Sn simulation predicts $P_{SB}^1 \approx 24$ GPa. About 2.25 $\mu$s later, a second shock of $P_{SB}^2 \approx 9$ GPa follows (a two-phase Sn EOS estimate). The two-wave tool incorporates “momentum trapping” [19, 20] techniques (Sn rings surrounding a central Sn disk, as shown in figure 3) and gives a uniaxial drive on the first shock, but the arrival of the second shockwave introduces 2D features at later times. This two-shockwave tool is being used to study second shockwave ejecta phenomena to develop second shockwave ejecta models.

The simulations imply that the interval time between $P_{SB}^1$ and $P_{SB}^2 (\Delta t_{12})$, directly links to the composition and thickness of the composite booster, and that the direct manner to vary $P_{SB}^2$...
is through the variation of the anvil material. For example, simulations of a W anvil predict a higher peak $P^2_{SB}$ stress, but $P^1_{SB}$ is varied through use of different composite booster materials.

3. Experimental details

The hydrodynamic performance of the two-shockwave tool was evaluated with three hydro-tests at a local firing site. The experiments are identified as shot numbers 1755, 1756 and 1757, and all three packages were identical except for the composite booster. The composite booster was chosen to give one experiment with $P^1_{SB} < 19.5$ GPa, and at least one other with $P^1_{SB} > 19.5$ GPa. Because the CTH simulations implied that the TNT would give $P^1_{SB} > 19.5$ GPa we needed a low C-J state HE alternative to the TNT to drop one experiment to $P^1_{SB} < 19.5$ GPa.

We chose a calcitol booster that substitutes calcium for barium in baritol that gives $P_{CJ} \approx 16$ GPa. Thus the three experiments included three composite-booster configurations such that two of the configurations included 2 mm of PBX 9501 followed by either 5.5 mm of calcitol or 4.75 mm of TNT, and the third fielded 4 mm of PBX 9501 followed by 5.5 mm of TNT. These three geometries gave $P^1_{SB} = 18.5$, 24.5, 26.4 GPa on shots 1757, 1755, and 1756, respectively.

These pressures were estimated from the observed asymptotic first shock free-surface velocities of $u_{1fs} = 1.40$, 1.73, 1.83 mm/µs, respectively.

The three piece Sn target assemblies were 4 mm thick with a diameter $d \approx 94$ mm, and finished to roughness $R_a \approx 0.75$ µm at the Sn-vacuum interface, and to $R_a \approx 0.4$ µm at the Ti-Sn interface. The $R_a = 0.75$ µm finish had a dominant wavelength of $\lambda \approx 80$ µm and an amplitude of $h \approx 1.5$ µm resulting in a wavenumber-amplitude product of $kh = 2\pi h/\lambda \approx 0.12$. The Sn target was epoxied with ÅngströmBond to a solid Ti substrate that was 1.5 mm thick with $d \approx 152$ mm. This Ti and Sn target package was mounted on the acetal package that included the P076 HE lens, the 6.35 mm PBX 9501 booster, the 2 mm Ta anvil, and the composite booster(s) – the anvil and HE were diameter $d = 76.2$ mm, and the outer diameter

Figure 3. The left diagram shows the Sn target specifications for the three hydrodynamic tests, shots 1755, 1756 and 1757. The right diagram shows the LDV probe locations, with an estimate of the radius of the first and second shockwaves: $R(1^{st}) = 27$ mm and $R(2^{nd}) = 21.25$ mm. These radii are required to position the probes appropriately for meaningful measurements.
Table 1. Average velocimetry from the Chamber 8 shots.

| Experiment | LN probes/region | $u_{f1}$ (mm/µs) | $u_{f2}$ (mm/µs) | $\Delta t_{12}$ |
|------------|-----------------|-----------------|-----------------|-----------------|
| 1757       | 1-4             | 1.43 ± 0.04     | $u_{f1} + 0.7 \approx 2.13$ | 4.95 ± 0.35     |
|            | 5-7             | 1.36 ± 0.02     | N/A             | N/A             |
| 1755       | 1-4             | 1.73 ± 0.03     | $u_{f1} + 0.7 \approx 2.43$ | 5.70 ± 0.49     |
|            | 5-7             | 1.73 ± 0.00     | N/A             | N/A             |
| 1756       | 1-4             | 1.85 ± 0.01     | $u_{f2} + 0.5 \approx 2.35$ | 7.54 ± 1.70     |
|            | 5-7             | 1.80 ± 0.01     | N/A             | N/A             |

of the acetal package was 152 mm diameter. The physics package was completed with an acetal plug to cap the P076 HE lens.

The hydrodynamics were diagnosed with seven laser Doppler velocimetry (LDV) [21–23] probes mounted to an acetal top 40 mm above the Sn surface, and supported by an acrylic tube that completed a canister, allowing the evacuation of the package to pressures of $\approx 0.1$ torr.

3.1. Two-wave hydro-test velocimetry

The center velocimetry from each experiment is presented from left to right with increasing $P_{SB}$ in figure 4 ($P_{SB} = 18.5$, 24.5, and 26.4 GPa). Table 1 summarizes the LDV observations.

The important result from the LDV measurements is that the surface is apparently “lumpy” after the second shock so that $\Delta t_{12}$ varies by $\sigma(\Delta t_{12}) \sim O(0.5)$ µs. The variation of $\Delta t_{12}$ is related to the uneven damage beneath the surface of the spalled and cavitated Sn target subsequent to the first-shockwave compression and release. As the second shockwave arrives the time to compress the once shocked Sn varies, leading to a variation in the amplitudes of the second shock jump velocities.

4. Proton radiography experiments

We fielded the two-shockwave tool twice at the LANL pRad facility [24] in 2013, once into vacuum and once into 13.6 psia of Ne at room temperature. The experimental purpose was to evaluate the the RM bubble and spike dynamics in vacuum and gasses of twice shocked metals.

The physics packages for the pRad experiments were similar to those in figure 1, utilizing the same composite booster as shot 1755, but with differences in the target design. The target assembly included 1.5 mm of Ti supporting a 4 mm thick three-piece Sn target. The Sn, as in

Figure 4. Experimental 2-wave velocimetry measured from the target centers (LDV-1); Chamber 8 shots 1757 (left), 1755 (center), and 1756 (right).
the previous experiments, was cold rolled and of 0.9995 purity so that the average grain sizes were \(d_{\text{grain}} \sim \mathcal{O}(100) \) \(\mu\text{m}\) diameter, equiaxed and uniformly distributed throughout the material [25]. The Sn at the Ti-Sn interface was machined to \(R_a = 0.4 \ \mu\text{m}\), but the Sn-vacuum interface included four regions of perturbations on an otherwise smooth and flat diamond-turned surface finish (mirror like). The perturbation regions included seven wavelengths fixed at \(\lambda = 550 \ \mu\text{m}\) with varying amplitudes to give \(kh \in \{3/4, 1/4, 1/8, 1/2\}\), in descending order from top to bottom of the selected pRad images presented in figure 5. The four perturbation regions were separated by flat regions of 4 mm width. Velocimetry was measured above the three flat regions, and above the center of each perturbation region. Figure 6 shows the velocimetry from the pRad535 vacuum experiment, the neon experiment is pRad536.

The selected radiographs in figure 5 show the bubble and spike dynamics of the shocked Sn. The measured \(u_{fs}\) use the techniques described in [12] to predict with good agreement the spike tip velocities in the top four images of figure 6. The upper velocimetry images in figure 6 are from the perturbation regions, and the lower images from the flat regions.

The perturbation velocimetry shows that the interval times in the bubble regions were \(\Delta t_{12} \approx 4.5 \ \mu\text{s}\), but the flat region velocimetry gave \(\Delta t_{12} \approx 5.75 \ \mu\text{s}\). Further, the asymptotic bubble velocities are seen to be \(u_{fs}^1 \approx 1.7 \ \text{mm/\mu s}\), but \(u_{fs}^1 \approx 1.8 \ \text{mm/\mu s}\) in the flat regions. Unstable RM theory (see [12]) predicts that the asymptotic bubble velocities are twice the particle velocity, so this difference of \(\approx 0.1 \ \text{mm/\mu s}\) is important to understand and explain. Close inspection of \(u_{fs}^1\) in the flat regions reveals a nominal velocity jump of \(0.15 \ \text{mm/\mu s}\) approximately 0.3- to 0.4-\(\mu\text{s}\) after shockwave breakout. This could be caused by spall/cavitation in tension, or by edge effects at the surface interface between the perturbations and the flat regions. While the flat surfaces join at the peaks of the perturbation sine waves – zero slope – edge effects are nevertheless revealed in the \(t = 4.0 \ \mu\text{s}\) images in both the vacuum and gas images. The effects are seen at the flat-perturbed regions’ interfaces as large bubble penetrations unstably growing.

![Figure 5. pRad radiographs of twice shocked Sn targets that included large scale perturbations. The top images are into vacuum (pRad535), and the bottom into about 14 psia Ne (pRad536).](image-url)
into the Sn, and the flat regions appear elevated higher than they should be. This is the likely source of the differences in $\Delta t_{12}$ between the flat and perturbed regions, an undesired effect.

The flat region velocimetry on pRad535 implies a faster $u_{fs}^2$ than the image analysis reveals. At times $t > 7$- to 8-$\mu$s (after second shock) the LDV signals were reflecting from an ejecta layer beyond the flat surface, as clearly seen in the pRad images after 7.9 $\mu$s in figure 5. Nevertheless, pRad535 analysis reveals $u_{fs}^2 \approx u_{fs}^1 + 0.5$ mm/$\mu$s, more consistent with shot 1756 (see table 1).

Other key observations show that the RM unstable spikes in the vacuum data penetrate further than those in the Ne experiment. In the Ne experiment the spikes become diffuse. This is due to hydrodynamic drag and breakup of the spikes/sheets (ejecta).

As to whether the bubbles and spikes from the first shock seed RM unstable bubbles and spikes at the second shock, it is not obvious, but close inspection of the “red” boxes in all of the images ($kh = 1/8$) show the expected behavior, demonstrating the RM unstable physics is a mechanism of ejecta production for twice shocked metals. Work remains to be done to determine the effective amplitudes of the perturbations at the time of the second shock, but the wavelengths are the same. While RM unstable mass ejections are occurring, there are other mechanisms driving mass ejections seen in the flat regions. These appear to be caused by uneven subsurface damage caused by the first shock – cavitation and spall. As the spalled and cavitated surface is compressed by the second shock some of those layers break up on compaction.

Lastly, it is evident that the surface is quite flat prior to the second shockwave event, but with time subsequent to that event the surface becomes curved. The late time curvature is caused by release waves echoing within the shocked Sn. Thus, we have a mostly uniaxial drive.

5. Conclusions
We have presented simulations of an explosively driven, mostly uniaxial two-shockwave driver, and we applied the tool in three different experimental geometries. Experimentally we demonstrated an ability to vary the first shock amplitude by varying the composition of the composite booster. For example, the amounts of PBX 9501 in the experiments was varied, on one experiment we used calcitol, and on the other two experiments TNT was used in the composite boosters. The calcitol gave a first shock in the Sn below melt-on-release, followed by a second shock of about 1/2 the initial velocity jump.

An important observation from the table 1 velocimetry is that while the surface velocimetry after the first shock was quite uniform, with little variability, the velocity jumps at the
second shock, and the time intervals between first- and second-shocks varied dramatically with increasing $P_{SB}$. The implication is that damage to the Sn sample beneath the surface is nonuniform, causing wide variations in the second shock dynamics, and probably in the amount of ejecta produced in the second shock event.

We also applied the tool and diagnosed the surface dynamics with velocimetry and penetrating proton-radiography. The pRad data demonstrate that unstable RM physics is a driver of second shock mass ejections from twice shocked metals. However, we also see mass ejections caused by the compression of spalled and cavitated layers. Second shock ejecta models must account for such phenomena if they occur.

The simulations, hydro-tests, and applications demonstrate a two-shockwave tool that can be applied to study material damage of multiply shocked metals. Data from such experiments can be used to better understand damage processes in shocked materials.

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