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BURN FRONT AND REFLECTED SHOCK WAVE VISUALIZATION IN AN INERTIALLY CONFINED DETONATION OF HIGH EXPLOSIVE

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Abstract. Proton radiography was used to investigate the spatiotemporal evolution of the burn front and associated reflected shocks on a PBX-9502 charge confined between an outer cylindrical steel liner and an inner elliptical tin liner. The charge was initiated with a PBX-9501 booster and a line wave generator at 30° from the major axis of the ellipse. This configuration provides a large region where the high explosive (HE) is not within the line of sight of the detonation line and thus offers a suitable experimental platform to test various burn models and EOS formulations. In addition, the off-axis initiation allows for the burn fronts to travel around the charge through different confining paths. Simulations with the hydrocode PAGOSA were performed to assess the accuracy of several HE burn methodologies.

Keywords: Detonation, proton radiography, burn front, reflected shocks, PAGOSA.
PACS: 62.50.Ef, 47.40.Rs.

INTRODUCTION

When a high explosive (HE) charge is confined within a metallic assembly, the interaction between the burn front with the solid surfaces will produce a complex pattern of shocks and reflected shocks whose characteristics will depend not only on the equation of state (EOS) of the gaseous products of detonation but also on the strength properties of the confining materials. Accurate modeling of the spatiotemporal evolution of the shock pattern that ensues upon detonation of an inertially confined HE is a suitable test problem to establish the validity and efficacy of burn methods in modern hydrocodes. This challenge is accentuated when using an insensitive HE (IHE), which departs from an ideal HE in two respects. First, IHEs have a wider reaction zone, in the order of mm. Second, the propagation of the burn front slows down in the so-called shadow regions, i.e. regions within the HE that are not in the line-of-sight from where the detonation is initiated. We designed an asymmetric assembly in which PBX-9502 is confined between metallic cylinders. Using proton radiography, we recorded the development of the burn front and accompanying shock structure starting a few microseconds after initiation and ending after the HE shocks collided on the opposite side of the assembly. To perform quantitative comparisons with simulations, we defined a metric that captures departures in the timing and the shape of the shocks. With this metric, we were able to quantify the accuracy of several burn methodologies using the three-dimensional (3D) multimaterial hydrodynamics computer program PAGOSA [1]. PAGOSA is an Eulerian massively parallel code used to simulate the 3D dynamic behavior of materials (solid, liquid, or gases)

subjected to high-strain rates, like those produced by explosions and high velocity impact.

EXPERIMENTAL PROCEDURE

The experimental assembly consisted of a 10-cm long charge of PBX-9502 confined between an outer cylindrical steel liner and an inner elliptical tin liner as shown in Fig. 1. A plexiglass support fixture was fabricated to hold the assembly and photon Doppler velocimetry (PDV) probes.

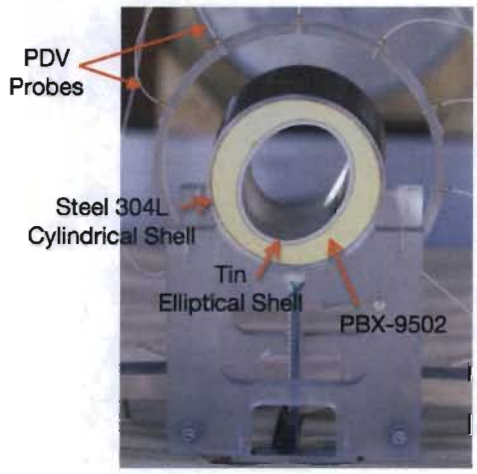

Figure 1. Assembly 3D view showing metal liners, IHE, booster, and location of the LWG.

Figure 2 shows a cross-section of the assembly. The outer radius of the IHE charge was chosen to fit within the field of view of the proton beam. A polymeric material 300 μm thick is used as bonding to hold the charge between the metal liners both of which are 3 mm thick.

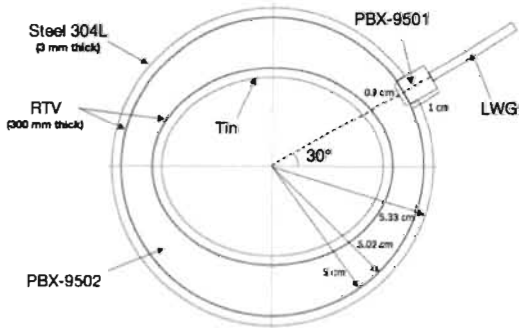

Figure 2. Cross-section of the assembly 3D view showing metal liners, IHE, and location of the LWG.

The charge was initiated with a PBX-9501 booster and a line wave generator (LWG) at 30 degrees from the major axis of the ellipse. This off-axis initiation allows for the burn fronts to travel around the charge through different paths and provides a large region where the HE is not within the line-of-sight from the booster detonation region and thus offers a suitable experimental platform to test various burn models and EOS formulations.

Data Digitization

The proton beam was tailored to detect density changes in the IHE located in the outer region of the field of view. Figure 3 shows a proton radiograph at 13.8 μs after booster initiation, where the burn fronts and reflected shocks from the outer steel liner are visible. It was observed that the intensity of the reflected shocks varied as a function of time, where the stronger shocks were observed at later times. In some cases, the liner reflected shocks were too weak to be clearly detected, particularly during the first 8 μs. This observation was consistent with PAGOSA numerical simulations.

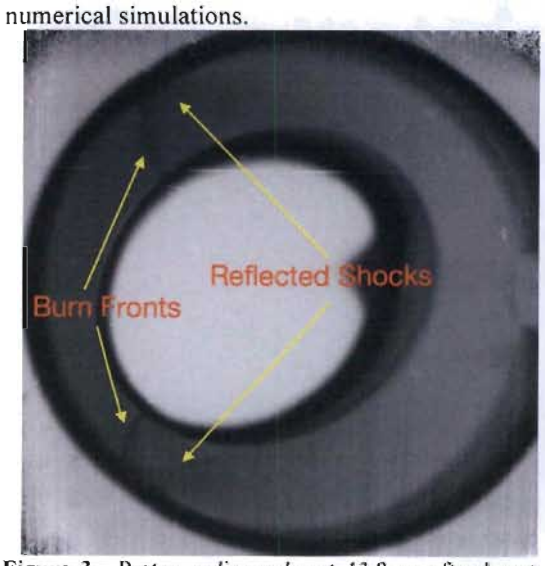

Figure 3. Proton radiography at 13.8 μs after booster initiation showing the burn fronts and reflected shocks from the outer steel liner.

A total of 20 frames were collected and digitized for quantitative comparisons with simulations. Figure 4 shows the digitized burn

front leading edges and the liner reflected shocks. We also digitized the HE reflected shocks (not shown below), which will be part of a future study. In principle, at a specified time there is a set of six isochrones, three of which are in the upper region ($0 \le \theta \le \pi$) and three in the lower region ($-\pi \le \theta \le 0$) in Fig. 4. Each set of three isochrones corresponds to a burn front and two reflected shocks (at the outer and inner liners). While we were able to extract the coordinates of all the burn front isochrones, only a few reflected shocks were strong enough to be unambiguously distinguished.

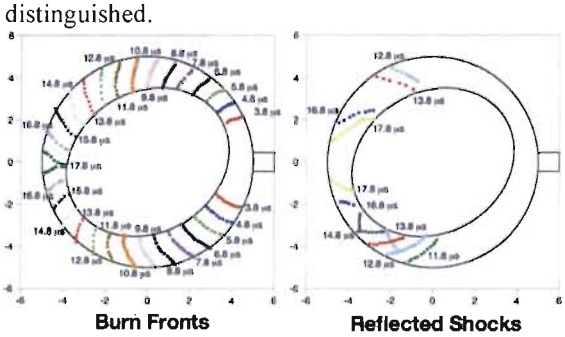

Figure 4. Digitized burn fronts and liner reflected shocks from proton radiographs.

Metric Definition

To quantify the accuracy of numerical simulations we introduced a metric that measures locally the temporal difference in shakes (0.01 μs) between the computed and the experimental shock isochrones. This metric can be defined as the time $\Delta\tau$ it takes for each point along the computed isochrone to reach the experimental one. Since the thickness (or radial extent) of the IHE domain is not constant as a function of angle we map this domain (in the r-θ plane) into a rectangular strip (in the s-θ plane) by introducing the dimensionless parameter s ($0 \le s \le 1$). Thus, the entire IHE region can be described by the function $r_{HE} = h(\theta, s)$ given by

$$h = \frac{(a+s)(b+cs)}{\sqrt{(a+s)^2 \sin^2(\theta - 30) + (b+cs)^2 \cos^2(\theta - 30)}} \qquad (1)$$

where a=4, b=3.3359, c=1.6641. At s=0, Eq. 1 represents an inclined ellipse by 30°, and at s=1 a circle of 5 cm radius. With this parametrization, the extent of each isochrone in the s-θ plane is $0 \le s \le 1$ regardless of its orientation in the r-θ plane. From numerical simulations, the isochrones are computed from the artificial viscosity $Q(r,\theta,t)$ at fixed points along lines of constant s (we mapped the IHE region with 1071 Eulerian tracers). When plotted as a function of time, each Q tracer has three maxima, one for the burn front and two for the reflected shocks. For the burn front, we find the time t_{mQ} at which the first maximum occurs. This allows us to generate the function $t_{mQ} = F(\theta, s)$. An isochrone at t_I in the s-θ plane is calculated by numerically inverting this function $\theta = F^{-1}(t_I, s)$. In the physical plane, the radial location of each point on the isochrone is given by $r = h\left(F^{-1}(t_I, s), s\right)$. Therefore, the metric function can be written as

$$\Delta\tau(t_{Exp}, s) = t_{mQ}(\theta_{Exp}, s) - t_{Exp} \qquad (2)$$

where θ_{Exp} is the angular coordinate of the experimental isochrone at s and $t = t_{Exp}$ and $t_{mQ}(\theta_{Exp}, s)$ is the simulated time that corresponds to the experimental θ_{Exp} and s. If $\Delta\tau > 0$ implies that the data is ahead of the simulation.

RESULTS AND DISCUSSION

Along each isochrone, we denote the spatial average over $0 \le s \le 1$ as $\Delta\bar{\tau}$ and the temporal average of $\Delta\bar{\tau}$ as $\langle \Delta\tau \rangle$. The latter provides a global spatiotemporal measure that indicates how well a simulation compares with the data. So far, we have run numerical simulations with PAGOSA to compare with two programmed burn algorithms, Huygens construction and detonation shock dynamics [2] (DSD), in both cases with the standard parameters for the JWL EOS were used. In addition, we tried the Huygens construction specifying two distinct regions of IHE, to differentiate that which is beyond the line-of-sight from the detonator. The abovementioned

simulations were carried out at 200 μm resolution. Finally, we ran simulations with the Forest fire (FF) reactive burn model [3] at several mesh resolutions from 500 to 150 μm. Figure 5 shows $\Delta\tau$ for the burn fronts in the lower region with when computed with FF.

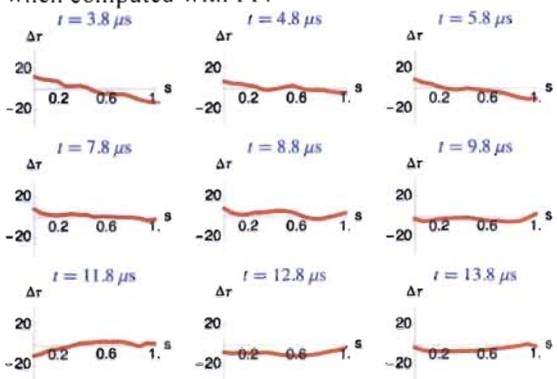

FIGURE 5. The metric $\Delta\tau$ for the region $-\pi \le \theta \le 0$ computed to compare between experimental isochrones and those computed with PAGOSA using FF.

For the same burn model, Fig. 6 shows $\Delta\bar{\tau}$ as a function of time. Notice that during the first 14 μs the simulation is in better agreement with the isochrones in the lower region (8 sh or less) and after that the opposite is true. The global spatiotemporal averages $\langle\Delta\tau\rangle$ are 6.6 and 5.7 sh for the upper and lower isochrones. A summary of the simulation results in terms of $\langle\Delta\tau\rangle$ is shown in Table 1. For the upper and lower reflected shocks at 12.8 and 16.8 μs, we obtained a $\langle\Delta\tau\rangle$ of 14.8 and 11 sh, respectively.

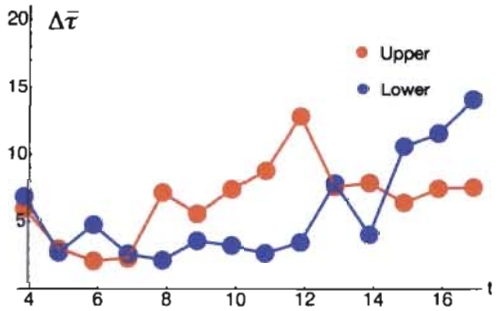

Figure 6. Averaged time departure along each isochrone $\Delta\bar{\tau}$ to compare between data and PAGOSA simulations using FF.

TABLE 1. Comparison of global spatiotemporal averages $\langle\Delta\tau\rangle$ in shakes for the burn fronts.

Burn Methodology	Upper Region	Lower Region
No Shadow Fraction	21.6	26.1
0.95 Shadow Fraction	8.4	10.6
Two IHE Regions	6.3	9.6
DSD	3.8	8.4
Forest Fire	6.6	5.7

CONCLUSIONS

FF and DSD provided the best agreement with the data. However, FF at 150 μm resolution produced similar departures from the data in both IHE regions. DSD yielded a greater discrepancy in the lower region (twice as large). All programmed burn schemes produced larger deviations in the lower region. While the agreement with the reflected shocks is acceptable, on average is twice as large as that for the burn fronts with FF.

ACKNOWLEDGEMENTS

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