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MIX AND INSTABILITY GROWTH FROM OBLIQUE SHOCK

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Abstract. We have studied the formation and evolution of shock-induced mix resulting from interface features in a divergent cylindrical geometry. In this research a cylindrical core of high-explosive was detonated to create an oblique shock wave and accelerate the interface. The interfaces studied were between the high-explosive/aluminum, aluminum/plastic, and finally plastic/air. Pre-emplaced surface features added to the aluminum were used to modify this interface. Time sequence radiographic imaging quantified the resulting instability formation from the growth phase to over 60 μs post-detonation. Thus allowing the study of the onset of mix and evolution to turbulence. The plastic used here was porous polyethylene. Radiographic image data are compared with numerical simulations of the experiments.

Keywords: Shock Mix, Hydrodynamic Instability, Shock Waves in Solids, Turbulent Mixing.
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INTRODUCTION

Our motivation was to understand the effect of interface perturbations in a high-explosive scenario. In particular, can they be utilized to create an early time mix region, how does this region evolve, and how does it affect subsequent later time turbulence? Furthermore, we were interested in whether these perturbations led to hydrodynamic instabilities and could be identified as such. In this investigation we used a typical divergent cylindrical geometry driven by high explosive (HE). Interface instabilities can increase the mixing layer and, if sufficiently strong, drive the expanding materials to an earlier turbulent state and influence degree of turbulence. In particular, increasing mix at the early stages of detonation response should result in a higher degree of turbulence much earlier in the explosion.

The experimental package used here is illustrated in figure 1. Fig 1a shows a three-dimensional cut-away of the experiment where we have used a solid cylindrical high-explosive core (LX-10) separated by a thin 1mm aluminum tube.

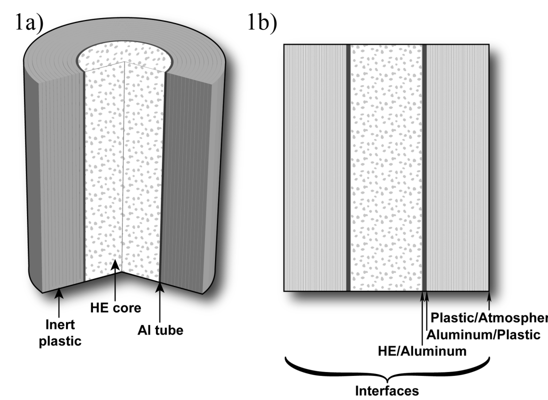

Figure 1. Schematic detailing interfaces of interest.

In these experiments the outer annulus was an inert porous plastic. Fig. 1b. highlights the interfaces of interest. These interfaces are shown here as smooth with no perturbations. The HE/plastic interface is separated by a thin layer of aluminum. As the aluminum is denser than either the HE reaction products or the plastic annulus, it can be used to track this interface. However, the aluminum complicates the experiment as it turns a single interface (HE/plastic) into two interfaces (HE/aluminum and aluminum/plastic). The second interface of interest is the plastic/air interface. Finally, an exterior case confined the package (not shown).

EXPERIMENTAL TECHNIQUE

This research utilized the Lawrence Livermore National Laboratory-High Explosives Application Facility (HEAF) with all experiments performed in the HEAF Spherical Firing Tank [1]. The principal diagnostic used was the Hydra X-Ray system [1]. Hydra utilizes time resolved point projection flash radiography to investigate the dynamic response of the materials to detonation and shock. We make use of the cylindrical geometry to image a time sequence of the dynamic processes with 25 ns exposure time.

Data from experiments with smooth interfaces show no signs of mix. Figure 2 is typical experimental data showing package response to detonation for smooth interfaces. Here the different layers of material retain their integrity and there is no intermixing at these early times (to about 100 μs). In these data the detonation is initiated from the bottom of the experiment and the detonation front is clearly seen in the upper portion of the data image in figure 2a. Figure 2a and b show the expansion of a smooth unperturbed aluminum liner at the HE/plastic interface. The thin aluminum can be used to track the interface as it expands. The material response is smooth and continuous with no indication of intermixing. Furthermore, the plastic/air interface exhibits no sign of mix after shock transit and breakout.

We devised this experiment to understand the effect of perturbations at the interfaces. Such perturbations could produce hydrodynamic instabilities that evolve and grow into a mix region. Mix is the interpenetration of two (or more) materials arising from instability growth due to perturbations in an accelerated interface. In this experiment we study mix in an accelerated interface between hot gases / reactions products from detonating explosive and porous polyethylene with a thin layer of aluminum separating these two regions. This interface is shocked and accelerated by the detonating HE. Hence, the resultant mix is due to a combination of Rayleigh-Taylor [2] and Richtmyer-Meshkov [3,4] instabilities.

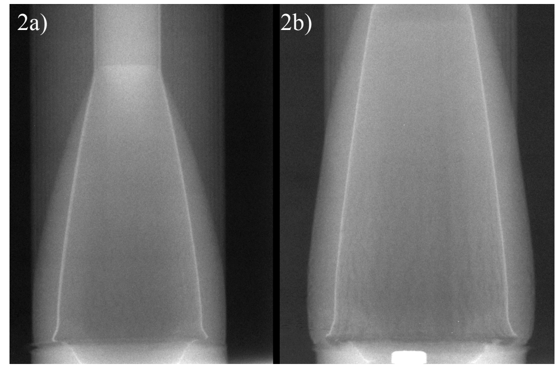

Figure 2. Radiography showing smooth transition of interfaces. Note detonation front in figure a) and shocked/compressed material envelope just outside the expanding aluminum liner cone trailing the detonation.

EXPERIMENT

The perturbed aluminum liner used in this experiment is visible in figure 3a. This part replaced the smooth aluminum tube at the HE/Plastic interface. The sinusoidal perturbations are intended to produce hydrodynamic instabilities for shock and acceleration induced mix. Unlike the plastic/air interface, the shock strength at the HE/Al/Plastic interface is very strong as it is in direct contact with the detonating HE. The aluminum contact with the outer plastic payload included air gaps in the valleys. As the plastic was not formed into the aluminum perturbations, there is good contact at the ridges, but not in the valleys. The corrugated aluminum interface was wrapped with plastic and inserted into a thin (3 mm thick) carbon fiber composite outer case. This outer case provides a high degree of confinement due to the strength of the carbon fiber composite, but generates no fragments to impair the radiography.

Figure 3 shows the time-sequence radiographic data from this experiment. In particular, the initial configuration (Fig. 3a), the onset of shock-induced mix at 17 μs (Fig. 3b), and finally the resultant system at 60.1 μs (Fig. 3c). In this experiment the detonation was initiated at the top. Figure 3b was taken with the detonation near the lower portion of the data image. This image clearly details the evolution of instabilities at the interface into mix structures and "pooling" of aluminum between these structures. As the shock is not normal to the interface, these structures are tilted downwards. This tilt can be used to determine the direction of the oblique shock. As these structures evolve, they create an intermix region in the expanding package. This material expansion is the dynamic response of the experiment to the detonating HE. It includes the shock response and the blast response from the expanding detonation reaction products.

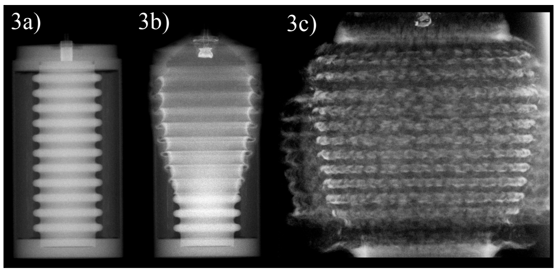

Figure 3. Experiment using aluminum liner with 0.25 inch sinusoidal perturbations. Core is hollow for HE insertion. Detonation is initiated from the top. Figure a) static image; b) 17.4 μs; and c) 60.1 μs. In b) the detonation front is about 75% through the HE. Aluminum interface trailing the detonation clearly shows mix structure development.

Figure 3c, at 60 μs post-detonation, is the latest time image. The "banding" observed in this image correlates to the initial perturbations in the aluminum liner. There is mixing within each band, but no intermixing between bands is observed (except for perhaps of the detonation products), so a fully turbulent state is NOT achieved at this point. These data detail the transition from emplaced perturbations at the HE/aluminum/plastic interface to instability formation / shock induced mix, to the creation of an expanding mix region.

This mix region would not exist without the initial perturbations in the aluminum liner and is direct response of the interface to the peak pressure and pulse width of the shock wave. The significant feature in this data is that the mix is striated along the lines of the original perturbations with no cross mixing! Our present interpretation of this is that there is indeed mix and a significant mix region, but not full turbulence at this point. However, the expanding mix region should facilitate the onset of turbulence.

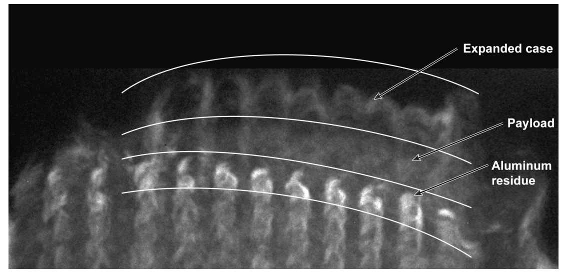

Figure 4. Magnification of mix region at 60.1 μs to show details. Although the detonation products are thoroughly mixed, residue from the aluminum liner, plastic payload, and carbon-fiber case are not and confined to distinct regions within the mix regime.

Figure 4 details the different regions in the mix zone caused by the pre-emplaced perturbations in the aluminum liner. These coincide with the different parts of the experiments. In particular, the outer case, plastic payload, and aluminum liner. Within the aluminum liner region are only the hot expanding gases and reaction products from the detonation. This mix region is drastically different than the data shown in figure 2 where each layer of material remains distinct post-detonation.

DISCUSSION AND SIMULATIONS

Figure 5 is a magnification of the hydrodynamic structures formed in this experiment. This is a key feature of our data that the model simulations should be able to match. Easily identifiable in this image are the Kelvin-Helmholz umbrella-like structures extending into the plastic.

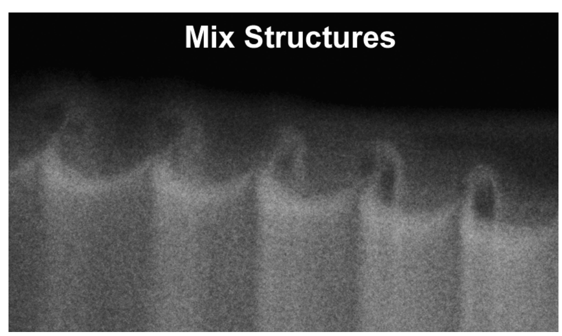

Figure 5. Magnification of data image at 17.4 μs detailing mix structures formed in the wake of detonation.

We have modeled this experiment using a 2-D arbitrary Lagrangian-Eulerian (ALE) code with CALE-like properties [5]. The explosive detonation is modeled Lagrangian and the rest Eulerian, so as to bring out any turbulence. As the detonation proceeds, it interacts with the aluminum that separates the HE from the plastic payload. This imparts a transverse shock wave to the aluminum that induces the formation of Kelvin-Helmholtz structures at the HE/aluminum/plastic interface. These structures develop into the plastic.

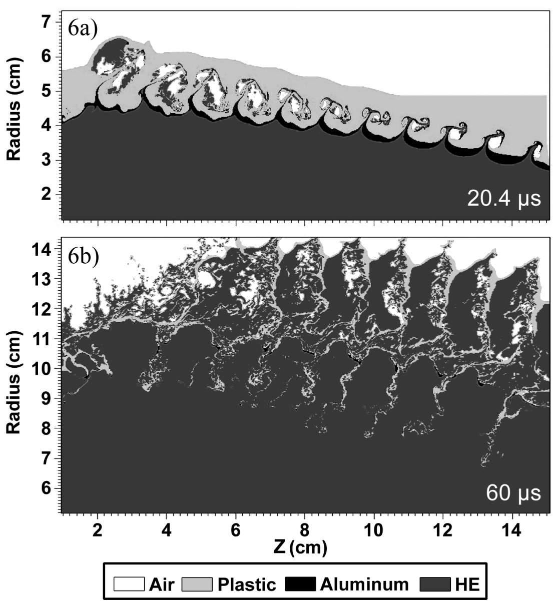

Figure 6. Numerical simulations with 2-D arbitrary Lagrangian-Eulerian (ALE) code.

Figure 6 shows a complete 2D calculation over the temporal range investigated. Figure 6a shows the model result at 20.4 μs, clearly showing the formation of shock induced mix structures similar to the data (Figures 3b and 5). The experimental data and numerical simulations diverge somewhat after 20 μs. The simulation in figure 6c shows a higher degree of turbulence and less localization of the aluminum than we see in the data (Figures 3c and 4).

SUMMARY/CONCLUSION

We show here that interface perturbations are necessary to create any significant mix region in experiments involving under 1 kg of HE at times up to about 60 μs. Our data suggest that hydrodynamic instabilities play a role, but some structures observed could be attributed to material jetting and not the formation and growth of instabilities.

We succeeded in creating a mix region that was due to emplaced perturbations at material interfaces. Perturbing the HE/aluminum/plastic interface clearly resulted in hydrodynamic instabilities that grew into identifiable mix structures. These structures are primarily shock induced. The growth of such structures is due to the peak pressure and pulse width of the oblique shock wave. The higher the peak pressure, the greater the shock induced mix, the longer the pulse width, the greater the acceleration induced mix.

Our data show that the mix region is essentially created and "frozen in", increasing with material expansion, not hydrodynamic instability growth. We do know from later time (> 500 μs) optical data that the expanding materials ultimately become turbulent. The role of this mix region in the onset of turbulence is still being investigated.

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