INVESTIGATION OF DISPERSIVE WAVES IN LOW-DENSITY SUGAR AND HMX USING LINE-IMAGING VELOCITY INTERFEROMETRY*

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Abstract. A line-imaging optically recording velocity interferometer system (ORVIS) has been used in gas-gun impact experiments to compare the mesoscopic scale response of low-density (65% theoretical maximum density) pressings of the explosive HMX to that of an inert simulant (granulated sugar). Dispersive waves transmitted through 2.27- to 6.16-mm-thick beds of the porous sugar typically include mesoscale fluctuations that occur on length scales consistent with those seen in 3-D numerical simulations. Conditions that approximate steady wave behavior occur at a sample thickness >4 mm. Transmitted wave profiles in HMX include complex effects of chemical reaction. For coarse-grain HMX samples, reaction expands vigorously over a narrow range (0.4-0.47 km-s^{-1}) of impact velocity. Localized regions of reaction growth are evident in the spatially resolved velocity-time data.

INTRODUCTION

Current numerical simulations (1) can explore in detail the correlation between microscopic properties and the response of heterogeneous materials to shock loading at mesoscopic scales, including spatial variations in stress and thermal fields (dispersive behavior). Experimental characterization of the shock response of these materials at the requisite scale via spatially resolved measurements of transmitted wave behavior in turn provides useful information for validation and calibration of the numerical models. Validated numerical descriptions of the detailed wave fields in these materials can be analyzed to determine accurate statistical properties (1). Hence, these methods provide a promising approach for acquiring the statistical distribution information needed to develop predictive continuum level descriptions of shock-loaded materials, including heterogeneous explosives.

In this paper, we describe experiments designed to explore the mesoscopic scale response of a common secondary explosive (HMX) in comparison with that of granulated sugar (sucrose), an inert explosive simulant. These tests seek to expand on a series of magnetic gauge studies of low-density sugar and HMX performed by Sheffield et al. (2,3) Experiments on low-density, porous sugar can address mesoscopic scale thermomechanical effects in the absence of rapid reaction. The sugar experiments discussed here primarily focus on the observed dispersive wave behavior as a function of sample thickness. The tests on HMX explore the complex, additional effects of chemical reaction in the shock response.

EXPERIMENTAL

Simultaneous line-imaging ORVIS and single-point VISAR measurements have been made on waves transmitted by pressed sugar (2.27-mm to 6.16-mm thick) and HMX samples (4-mm thick) in a gas gun target design very similar to that used in the previous magnetic gauge studies (2,3). A
The schematic diagram of this design is shown in Fig. 1. The target assembly consists of a Kel-F impactor and a Kel-F target cup containing sugar or HMX pressed to 65% theoretical maximum density (TMD). The porous bed is confined by a 0.225-mm-thick buffer layer of Kapton and an aluminized PMMA interferometer window. The buffer is used to mitigate the loss in reflected light intensity that typically occurs upon shock arrival at the window. To achieve consistency in preparation of the low-density, porous samples, both mass and volume of the material were carefully controlled.

Sugar samples were prepared from coarse, granulated material. A description of the particle size distribution both as received and after pressing and release has been reported previously (4). The largest weight fraction (~60%) of the granulated sugar resides in a grain size range of 250-425 μm. A significant amount of grain crushing occurs even at the low pressing density used in this study. HMX samples were prepared from three different materials: [1] a coarse-grained lot of Holston batch HOL 920-32 (mean particle size near 120 μm), [2] a fine-grain sieved sample (38-45 μm), and [3] a coarse-grain sieved sample (212-300 μm).

The line-imaging ORVIS used in this study is a compact system that combines the interferometer optics, laser source (2W NdYVO₄ cw laser), and streak camera/intensifier/CCD detector on a single 2’ x 6’ optical breadboard. Detailed discussions of the instrumentation, the optical coupling to the gas gun target chamber, and image data reduction methods are available elsewhere (4). Single-point VISAR data were obtained using a dual-delay-leg, “push-pull” assembly.

RESULTS AND DISCUSSION

Low-Density Sugar Experiments

As described previously (4), results from both VISAR and line-imaging ORVIS are generally consistent with the systematically varying dispersive behavior of wave profiles vs. impact velocity reported by Sheffield et al. (2). This includes comparable measured shock and particle velocities as well as rise times in the transmitted wave that decrease from 700 ns to 200 ns as impact velocity increases from 0.3 to 0.7 km-s⁻¹.

respectively. The spatially resolved ORVIS data also reveal mesoscopic scale velocity variations (both transverse and longitudinal wave structures). The length scale of the wave fluctuations can vary over a wide range (~10-200 μm) depending on the local particle size distribution.

Instructive comparisons can be made between the observed wave profiles and those generated by the 3-D simulations. A description of computational methods and results from numerical simulation of a shock-loaded 2.27-mm-thick sugar sample are given in Reference 1. The computations predict rapid deformation at material contact points in the sample. Both stress and temperature fields display large amplitude fluctuations, arising from the effects of shocks interacting with individual material surfaces and multiple crystal interactions. Figure 2 displays a time sequence of temperature fields along a midplane cross-section of the sugar bed after impact at 0.5 km-s⁻¹. Similar dispersive wave effects are evident in the stress field contours (not shown). Of particular interest is a crystal penetration event that occurs at the region marked...
by an arrow. Such effects contribute to loss in reflected light intensity and drive the need to view transmitted waves through a thin buffer material.

For comparison with experimental data, particle velocity was computed at approximately 50 "tracer" points along a line segment located at the Kapton/PMMA interface. As shown in Fig. 3a, the velocity-time profile at the interface displays complex transverse mode structure (even after transmission through the buffer) in addition to a ~100-ns rise time in the wave. Representative spatially resolved velocity-time plots from line-imaging ORVIS data are also presented in Fig. 3b and 3c. In general agreement with simulation, waves transmitted through 2.27-mm and 4-mm-thick sugar beds, respectively, display significant transverse wave structure and early peaks in particle velocity (arising from a shock impedance mismatch between porous sugar and the homogeneous buffer material) followed by late-time velocities near 0.25 km-s$^{-1}$.

For 2.27-mm-thick samples, the rise time of the transmitted wave is in good agreement with simulation. A clearly longer rise time is seen in the 4-mm case. These results point to non-steady wave behavior at the reduced sample thickness.

The issue of "steadiness" in the wave behavior vs. sample thickness is important in defining the computational domain needed to achieve representative conditions in the low-density material. Accordingly, we have extended our tests to include thicker (6.16-mm) samples. Fringe records of the wave transmitted by three different thicknesses of sugar are displayed in Fig. 4. The rise time in waves generated in the two thicker samples appear to be very similar. The transition in the 2.27-mm-thick sample is (as also indicated above) more abrupt, especially with respect to the duration of the "foot" of the ramp. A compilation of rise times (estimated as the time for wave velocity to progress from 10% to 90% of the maximum level) from both VISAR and ORVIS measurements is shown in Fig. 5. These data suggest that relatively steady wave behavior may be obtained for sample thickness $\geq$4 mm. It must be noted, however, that the overall wave behavior actually consists of a superposition of many wavelets, a phenomenon that is highly statistical in nature.

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**FIGURE 3.** Comparison of (a) predicted and (b) measured velocity profile of wave transmitted by 2.27-mm-thick sugar sample. The measured velocity profile transmitted by a 4-mm-thick sample is shown in (c). Impact velocity near 0.5 km-s$^{-1}$. A 900-ns duration of time is plotted in all three cases.

**FIGURE 4.** Line ORVIS image data showing transmitted wave from (a) 2.27-mm, (b) 4-mm, and (c) 6.16-mm-thick sugar, respectively; impact velocity near 0.5 km-s$^{-1}$.

**FIGURE 5.** Rise time of wave transmitted by 65% TMD sugar as a function of sample thickness.
Low-Density HMX Experiments

As discussed by Sheffield et al. (3), compaction waves at levels below the threshold for reaction in porous HMX behave in a manner similar to those in sugar. At levels above the threshold for initiation, chemical reaction causes the wave to accelerate and to become steeper as it travels. Line-imaging ORVIS can reveal interesting details of the initiation and reaction growth at mesoscopic scales.

A spatially resolved velocity-time profile for 65% TMD HMX (HOL920-32) subjected to impact at 0.4 km-s⁻¹ is shown in Fig. 6. The wave is diffuse with a rise time ~150-200 ns, slightly faster than that reported by Sheffield et al. (3) Also evident are localized regions of modest wave growth, reflecting the onset of exothermic reaction. This localized wave growth is a consistently observed feature of low-density HMX at impacts slightly above threshold for onset of reaction. Figure 7 provides another example, displaying a plot of the wave behavior from three different regions of the sieved 212-300μm material under impact at 0.4 km-s⁻¹. Sample particle size is also directly reflected in the amplitude and frequency of wave fluctuations seen in this plot (i.e., the sieved, coarse grained sample exhibits prominent low-frequency fluctuations in its wave profile).

The VISAR and ORVIS results also reveal that the coarse grained HMX materials (HOL920-32 and sieved 212-300μm) display a sharp increase in reactivity over a fairly narrow range of impact velocity (0.4-0.47 km-s⁻¹). In contrast, the transmitted wave profiles from the finer 38-45μm sieved HMX exhibit little evidence of exothermic reaction under the same conditions. The different

![FIGURE 6. Spatially resolved transmitted wave profile from 65% TMD HMX; 0.4 km-s⁻¹ impact velocity.](image)

FIGURE 6. Spatially resolved transmitted wave profile from 65% TMD HMX; 0.4 km-s⁻¹ impact velocity.

**TABLE 1.** Peak Particle Velocities of Transmitted Waves from Low-Density HMX (as determined by VISAR and line-imaging ORVIS)

<table>
<thead>
<tr>
<th>Impact Velocity (km-s⁻¹)</th>
<th>Holston Batch HOL920-32</th>
<th>212-300μm Sieved HMX</th>
<th>38-45μm Sieved HMX</th>
</tr>
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<tr>
<td>0.4</td>
<td>0.25</td>
<td>0.38</td>
<td>0.23</td>
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<tr>
<td>0.425</td>
<td>&gt;0.3</td>
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<tr>
<td>0.47</td>
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<td>0.275</td>
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<td>0.53</td>
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REFERENCES