LA-UR-97-2992

Title: **Detonation Wave Profiles in HMX Based Explosives**

Author(s): R. L. Gustavsen
S. A. Sheffield
R. R. Alcon

Submitted to:

DETONATION WAVE PROFILES IN HMX BASED EXPLOSIVES[†]

R. L. Gustavsen, S. A. Sheffield, and R. R. Alcon

Los Alamos National Laboratory, Los Alamos, NM 87545

Detonation wave profiles have been measured in several HMX based plastic bonded explosives including PBX9404, PBX9501, and EDC-37, as well as two HMX powders (coarse and fine) pressed to 65% of crystal density. The powders had 120 and 10 μm average grain sizes, respectively. Planar detonations were produced by impacting the explosive with projectiles launched in a 72-mm bore gas gun. Impactors, impact velocity, and explosive thickness were chosen so that the run distance to detonation was always less than half the explosive thickness. For the high density plastic bonded explosives, particle velocity wave profiles were measured at an explosive/window interface using two VISAR interferometers. PMMA windows with vapor deposited aluminum mirrors were used for all experiments. Wave profiles for the powdered explosives were measured using magnetic particle velocity gauges. Estimates of the reaction zone parameters were obtained from the profiles using Hugoniots of the explosive and window.

INTRODUCTION

In the early 1940's Zel'dovich, von Neumann, and Doering independently advanced the theory of steady one-dimensional (1-D) detonation beyond the earlier Chapman Jouguet (CJ) theory by finding a solution of the flow equations with a resolved chemical reaction zone(1). In this model, called the ZND model, the detonation process consists of a shock wave that takes the material from its initial state to a "von Neumann" spike point on the unreacted Hugoniot. The ZND reaction zone is traversed by proceeding down the detonation Rayleigh line from the spike point to the CJ condition, i.e., the fully reacted state. An interesting characteristic of ZND theory is that the pressure and particle velocity decrease from the spike point to the CJ state, even though energy is being released by the chemical reaction in this region. From the CJ state the explosive products expand in a Taylor wave. ZND theory (and detonation in general) is discussed in Ref. 2.

The reaction zone time (time to go from the spike point to the CJ state) is thought to be a sensitive function of the chemical composition of the explosive, as well as its density and grain size. However, since very little is known about the chemistry occurring or the explosive grain crushing and burning characteristics in the detonation environment, the effect of various parameters is unknown. It is in search of some understanding in this area that this study was made.

Reaction zone studies have been made in the past using a number of different techniques to directly or indirectly observe the reaction zone in a detonating explosive. These have included plate-push experiments, detonation front curvature measurements, emitted light measurements, and laser velocity interferometry measurements. In all measurements, the front is perturbed by the measurement.

Laser velocity interferometry has yielded the best reaction zone measurements. In this method, a window with a thin, diffusely reflecting mirror is placed in contact with the explosive which is detonated. Laser light reflected from the mirror is Doppler shifted when the velocity changes and an

[†] Work performed under the auspices of the U.S. Dept. of Energy.

interferometer transduces this into particle velocity of the interface vs. time. Several studies have used this technique in various interferometer setups (ORVIS and Fabry-Perot) to estimate reaction zones in various explosives(3-5). Time resolution can range from 10 ns down to subnanosecond, depending on the interferometer and the recording technique.

This study is an application of the VISAR interferometer technique to the study of high-density plastic-bonded HMX-based explosive reaction zones. In addition, the electromagnetic gauging technique is used to study reaction zones in two low density pure HMX explosives.

EXPERIMENTAL DETAILS

VISAR Experiments on High Density Explosives

Materials – Three different plastic bonded HMX based high explosives were used in this part of the study: PBX9501, PBX9404, and EDC-37. PBX9501 has 95wt% HMX and 5% binders. The material used had a density of 1.83 g/cm^3. PBX9404 has 94wt% HMX and 6% binders. The material used here was made in 1987 and had a density of 1.84 g/cm^3. EDC-37 has 91wt% HMX and 9% binders and the material used had a density of 1.84 g/cm^3. In all three materials, some of the binders were energetic, i.e., nitrocellulose or some other material with nitrate groups.

Experimental Setup – The experimental setup for the high density explosives is shown in Fig. 1. Gas gun driven projectiles faced with Vistal (a pressed alumina ceramic) produced planar, sustained shock input conditions to the explosives which were 50.8 mm diameter and 12.5 mm thick.

A polymethylmethacrylate (PMMA) window was used as the interferometer window in all experiments. (Two kinds were used; Rohm and Haas Type II UVA Plexiglas was used on the PBX9501 and Polycast PMMA made to Mil-Spec. P5425D was used on the PBX9404 and EDC-37.) The window was lapped flat, polished to a slightly diffuse finish, and then aluminum was vapor deposited on it. An 8 μm thick sheet of Kapton was epoxied on top of the aluminum to protect it. An explosive cylinder was then glued to the window. The combined thickness of all glue bonds for a typical experiment was a few microns.

Impact velocity for all experiments was about 0.92 mm/μs resulting in an input to the explosive of about 6 GPa. At this input, runs to detonation were, respectively, 3.2 mm for PBX9404, 3.8 mm for PBX9501, and 6.8 mm for EDC-37, so a planar

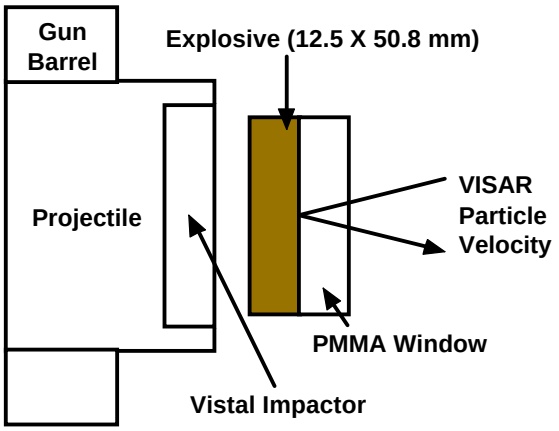

FIGURE 1. Cross section view of the projectile and target.

detonation traveled 5.7 to 9.3 mm before colliding with the window.

VISAR Setup – Interface particle velocity measurements were made using two VISARs set at different velocity per fringe constants; 1.818 and 0.806 mm/μs/fringe respectively. The particular VISARs used were Valyn Model VLNV-04-C (6). These VISARs have photomultiplier tubes that convert the light to electrical signals which were recorded by a Tektronix TDS-684 digitizer at 0.4 ns/point.

Several experiments were done in an effort to determine the time resolution of the photomultiplier/ digitizer recording system. A ring-up experiment in a sapphire plate was used to produce a series of sharp shocks which were recorded by the VISAR system. Analysis of this and other experiments led us to estimate that the time resolution of the system is about 2.5 to 3 ns.

Magnetic Gauge Experiments on Porous HMX

Materials - Two different batches of HMX powder were used in this part of the study: "*Coarse*" HMX (Holston HMX Lot 920-32) has particles that look like granulated table sugar and a mean particle size of about 120 μm; "*Fine*" HMX (Holston HMX Lot HOL-83F-300-023) has particles that look like powdered sugar and a mean particle size of about 10 μm. Thus, these two batches have about an order of magnitude difference in the average particle size. Additionally, the coarse HMX has crystals with sharp corners and edges. The fine HMX has particles with a rounded appearance indicating that this material was probably prepared by milling.

Experimental Setup – The experimental setup for the low density HMX experiments has been described earlier(7,8). Briefly, gas gun driven projectiles were used to obtain planar sustained-shock inputs. HMX powder was confined in sample cells which had a polychlorotrifluoroethylene (Kel-F) front face and a polymethylmethacrylate (PMMA) cylindrical plug back. The front face was attached with screws to a Kel-F confining cylinder with an outside diameter of 68.6 mm and an inside diameter of 40.6 mm. The pressed HMX (between the Kel-F and PMMA) samples were nominally either 6 or 8 mm thick with a nominal density of

1.24 g/cm^3. The back plug was pressed into the Kel-F confining cylinder to compact the HMX and was held in place with an interference fit. Magnetic particle velocity "stirrup" gauges (with 10 mm long active ends) were epoxied to the Kel-F front and the PMMA back so they would contact the HMX. Particle-velocity histories were measured at both the front and back of the HMX sample, although only the back gauge records will be presented here. Wave profiles were recorded on fast digitizers.

Projectiles faced with Vistal impacted the Kel-F target face with a velocity of about 0.77 mm/μs producing inputs of about 2.5 GPa to the HMX. Full detonation is reached in runs of about 3 mm(9).

RESULTS

Five experiments were completed on the high density explosives; two each on PBX9501 and PBX9404 and one on EDC-37. Figure 2 shows the best particle velocity profiles obtained for each of the explosives. All have a spike followed by a reaction zone and then the Taylor wave. The spikes are at nearly the same particle velocity. This might be expected since all three explosives are similar in chemical makeup. However, we may not be able to resolve differences because of the 2.5-3 ns resolution of this system. The profile shapes after the spikes are somewhat different, with the PBX9404 remaining slightly higher than EDC37 and PBX9501. It is not yet known if these differences are significant; more identical experiments will have to be completed on each material to demonstrate a difference.

In all the experiments, the PMMA windows went opaque, but the PBX9501 experiments (using Rohm and Haas UVA II windows) were analyzable for about 1.3 μs while those for PBX9404 and EDC-37 (using Polycast windows) were only analyzable for the first 200 ns. This is almost certainly due to differences in the two types of PMMA, and will be looked into more carefully in the future. We note that Seitz et al. (4) used only Rohm and Haas UVA II windows in their reaction zone studies of PBX9502.

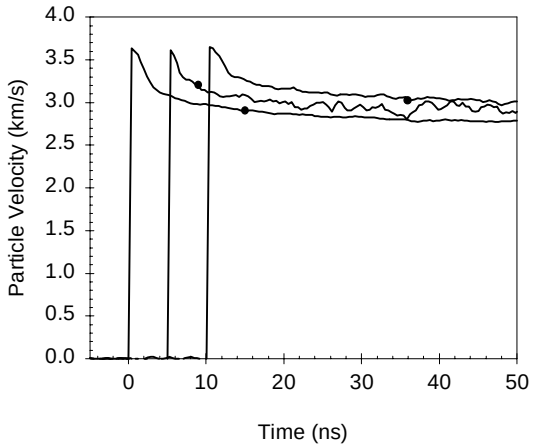

FIGURE 2. Wave Profile obtained for PBX9501, EDC-37, and PBX9404 shown left to right, respectively. The time origins for the EDC-37 and PBX9404 profiles have been shifted. The calculated ends of the reaction zones are shown as dots (see text).

Figure 3 shows detonation wave profiles obtained in the 1.24 g/cm^3 coarse and fine particle HMX. The records shown are for 8-mm thick samples initiated with about 2.5 GPa. Similar records were obtained for 6 mm thick samples. Estimates based on sample thickness and a detonation velocity of 6.55 mm/μs indicate that the fine particle HMX achieves detonation in about 100 ns, and the coarse particle HMX in about 600 ns. The time resolution is obviously much lower than the VISAR waveforms but the gauges are robust enough to record for several microseconds.

The profiles, particularly for the coarse HMX, are not characteristic of ZND type flow. This is probably because of the extreme heterogeneity of the processes that are occurring as the detonation moves through the porous bed of HMX. It is not known what causes the considerable (incredible) noise on the records but we surmise it is caused by crystal breakage, reaction, and detonation processes. The detonation front, particularly in the coarse HMX, is probably very rough. The fine particle profiles were reproducible from shot to shot but the coarse particle profiles were not.

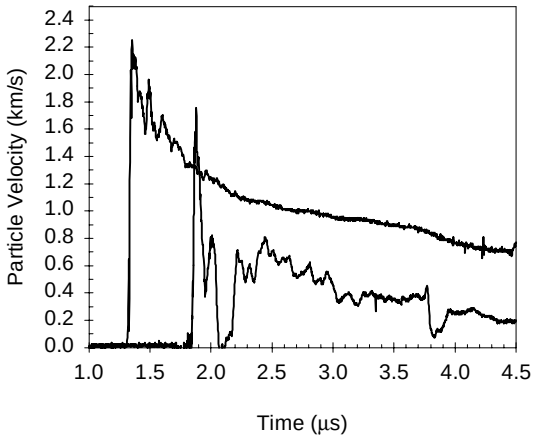

FIGURE 3. Detonation wave profiles obtained for fine particle and coarse particle HMX shown left to right respectively. The time difference is the difference in initiation times.

ANALYSIS

We have analyzed the waveforms in an attempt to estimate reaction zone parameters from the data. This has been done by finding Hugoniot and isentrope intersections in the pressure-particle velocity plane. The relevant Hugoniots and the product isentrope for PBX9501 are shown in Figure 4. As one might suppose, the parameters obtained are only as good as the assumptions made for the equations of state.

Briefly, the spike point is determined by the intersection of the Rayleigh line and the unreacted PBX9501 Hugoniot. This is matched down to the PMMA Hugoniot. Similarly, the product isentrope is used to match from the estimated CJ point to the PMMA Hugoniot. This gives the points S:M and CJ:M in particle velocity. These data are then used to determine the nearness of the measurement to the spike point anticipated and to determine the reaction zone time based upon when the particle velocity goes below the CJ:M condition. Doing the analysis in this way leads to estimates of the von Neumann spike pressure of slightly over 50 GPa and reaction zone times (lengths) of 15 ns (130 μm) in PBX9501. A similar analysis for the other two materials leads to widely varying data because the Hugoniots (both unreacted and products) are not well known, particularly for EDC-37. Until further experiments are done, we will only estimate that the spike pressure for this class of materials is near 50 GPa and the reaction zone time (length) is about 15-25 ns (130 to 250 μm) long.

Reaction zone lengths and times could not be determined for the porous HMX samples. The fine particle HMX waveform appears to have reached a peak midway between CJ and the calculated spike point. The coarse particle HMX peak just barely reaches the estimated CJ point.

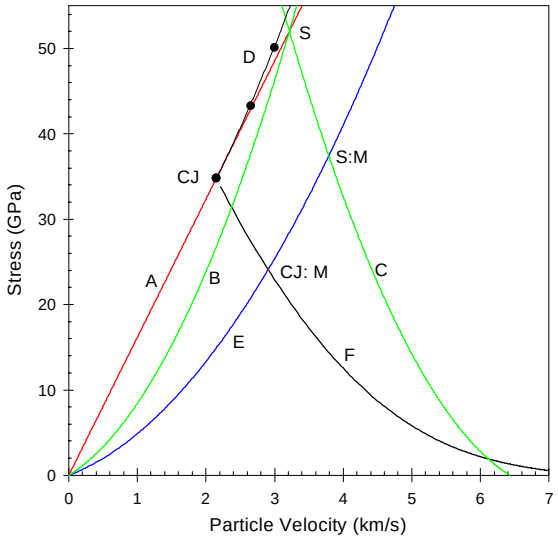

FIGURE 4. Hugoniots and isentropes relevant to calculating the reaction zone parameters. PBX 9501 is shown here. Explanations of the labels follow. (A)Detonation Rayleigh line. (B) Unreacted Hugoniot for the explosive. (C) Reflection of the unreacted Hugoniot for the explosive. (D)Explosive products Hugoniot. (E) PMMA window Hugoniot. (F)Explosives products isentrope calculated using the JWL EOS. (S)ZND spike point. (S:M) Spike point matched onto the PMMA Hugoniot. (CJ) Chapman-Jouguet or CJ state. (CJ:M) CJ state matched onto the PMMA Hugoniot. The matched spike and detonation points are those which would be observed.

ACKNOWLEDGMENTS

Robert Medina is thanked for his assistance operating the gas gun. Mel Baer of Sandia National Laboratory is thanked for useful discussion regarding the detonation profiles in porous HMX.

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