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SHOCK INITIATION EXPERIMENTS ON RATCHET GROWN PBX 9502

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Abstract. This study compares the shock initiation behavior of PBX 9502 pressed to less than nominal density (nominal density is 1.890 ± 0.005 g/cm^3) with PBX 9502 pressed to nominal density and then "ratchet grown" to low density. PBX 9502 is an insensitive plastic bonded explosive consisting of 95 weight % dry-aminated tri-amino-tri-nitro-benzene (TATB) and 5 weight % Kel-F 800 plastic binder. "Ratchet growth" – an irreversible increase in specific volume – occurs when an explosive based on TATB is temperature cycled. The design of our study is as follows: PBX 9502, all from the same lot, received the following four treatments. Samples in the first group were pressed to less than nominal density. These were not ratchet grown and used as a baseline. Samples in the second group were were pressed to nominal density and then ratchet grown by temperature cycling 30 times between -54°C and +80°C. Samples in the final group were pressed to nominal density and cut into 100 mm by 25.4 mm diameter cylinders. During thermal cycling the cylinders were axially constrained by a 100 psi load. Samples for shock initiation experiments were cut perpendicular (disks) and parallel (slabs) to the axial load. The four sample groups can be summarized with the terms *pressed low*, *ratchet grown/no load*, *axial load/disks*, and *axial load/slabs*. All samples were shock initiated with nearly identical inputs in plate impact experiments carried out on a gas gun. Wave profiles were measured after propagation through 3, 4, 5, and 6 mm of explosive. Side by side comparison of wave profiles from different samples is used as a measure of relative sensitivity. All reduced density samples were more shock sensitive than nominal density PBX 9502. Differences in shock sensitivity between ratchet grown and pressed to low density PBX 9502 were small, but the low density pressings are slightly more sensitive than the ratchet grown samples.

Introduction

For shock initiation of an explosive of fixed composition, it is well known that reductions in density cause an increase in shock sensitivity.[1] Density reductions are the inverse of an increase in the void content. A given void content can be produced by many small voids or by a few large voids. Campbell et al.[1] postulated "hot spots" as the microscopic mechanism responsible for shock initiation in pressed explosives. One hot spot mechanism is that of a shock wave sweeping over a void. More void might result in more small hot spots or in a few larger hot spots. The hot spot size and concentration (or number density) are known to influence the shock sensitivity of the explosive.

Pressed explosives based on tri-amino-tri-nitrobenzene (TATB) are known to undergo "ratchet growth" – irreversible density reduction – when they are temperature cycled.[2]This is thought to result from the graphite like structure of the TATB crystal and its very anisotropic coefficient of thermal expansion (CTE).[2,3] Until recently, it has not been known how ratchet growth affected the pore size distribution and structure in a TATB based explosive. Mulford and Romero[4] obtained micrographs of PBX 9502 thermally cycled 5 times to +216°C. Mulford and Romero concluded that the voids emphwithin TATB grains increased in both size and number.

Thompson et al.[5] recently extended this work using Computed Tomography instruments. Their work indicates that PBX 9502 cycled 30 times between -54°C and +80°C contains many more small voids than PBX 9502 pressed to nominal density or PBX 9502 pressed to a reduced density. The voids were also more uniformly distributed in the ratchet grown specimens. Ratchet grown specimens were also found to have reduced strength and modulus. These results are consistent with damage accumulation in the ratchet grown PBX.

Salyer[6] has studied detonation failure in PBX 9502 at nominal density, pressed low, and after ratchet growth. These experiments observed propagation of an initially steady detonation in 20° cones. The pressed low and ratchet grown samples in Salyer's study had precisely equal densities of 1.863 g/cm^3. Salyer found that detonations in thermally cycled PBX 9502 propagated in smaller diameters and with less velocity reduction than in either the pressed low PBX or the nominal density PBX. His conclusion was that the hot spots produced in the ratchet grown PBX 9502 were more effective at supplying energy to the detonation front and keeping the detonation going.

To date, little has been done to study shock initiation in ratchet grown TATB based explosives. The known exception, the work of Mulford and Romero[4] produced inconsistent results: Four experiments with nearly identical 10.9 GPa input pressures resulted in times to detonation ranging from 1.2 - 1.9 μs. Furthermore, Mulford and Romero's PBX 9502 samples were ratchet grown by cycling to temperatures exceeding +200°C, a temperature far outside that which an explosive would see under "environmental" conditions. The goal of our study, is to add to the results of Mulford and Romero[4], and in particular, to compare the response of ratchet grown PBX 9502 with material pressed to a similar density.

Experiment

Material Preparation

All samples for this set of experiments were made using recycled molding powder lot HOL88A891-006. Table 1 shows some basic properties of this lot including the TATB particle size and surface area. Charges were isostatically pressed using an MT-A42 hollow hemispherical mold with a steel inner mandrel. Table 2 shows pressing parameters for the three charges used in this study. (Charges are numbered using the same scheme used by Thompson et al.[5] Charge #3 was pressed to low density and not ratchet grown and is used as a baseline.

Cylinders or rods, 25.4 mm diameter by about 100 mm long were cored out from the hemispherical pressings: the core axes were perpendicular to the equatorial plane of the hemisphere. Cylinder densities were measured by the water immersion method. Cylinders from charges #2 and #4 were next thermally cycled 30 times between -54°C and 80°C. Cylinders from charge #2 were cycled with no confinement, while cylinders from charge #4 were confined by imposing a 100 psi load on the end of the cylinders. From charge #4, therefore, the ratchet growth would be in the cylinder's radial direction. After thermal cycling, densities were again measured. Densities listed in table 2 are those of the samples used for the shock initiation experiments.

Samples for the shock initiation experiments were cut from the 25.4 mm diameter by 100 mm long rods as shown in Figure 1. Disk shaped samples, as shown in the left hand side of Fig. 1, were cut from the pressed low hemisphere and the from an unconfined ratchet grown sample.

For the axially confined ratchet grown cylinders, the growth is clearly anisotropic. There was some possibility that the void distribution or void orientation might also be anisotropic. If this were true,

Table 1. Properties of PBX 9502 Lot Hol88A891-006.

Particles < 45 μm	Particles < 20 μm	Surface area, BET	Surface area, photoelometer
74.0 %	34.6%	12199 cm^2/g	4978 cm^2/g

Table 2. Pressing parameters for PBX 9502 charges used in this study.

Charge ID/description	Charge #3 pressed low baseline	Charge #2 pressed high ratchet grown, no load	Charge #4 Pressed high, ratchet grown 100 psi axial load
Pressing temp. (°C)	110	110	110
Pressing pressure (ksi)	10	20	20
No. of cycles	4	4	4
Dwell time (min.)	5	5	5
Density (g/cm^3)	1.867 ± 0.004	1.893 ± 0.002	1.896 ± 0.001
Post ratchet growth	NA	1.870 g/cm^3	1.876 g/cm^3

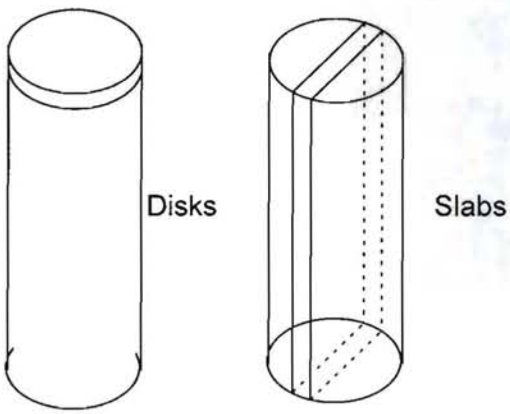

Fig. 1. Schematic showing how samples for shock initiation experiments were cut from cylinders of PBX 9502. Disks were cut from charges 2, 3, and 4. Slabs were cut only from charge 4.

then it might also be possible to observe anisotropic initiation behavior. To explore this possibility, we cut some samples from charge #4 cylinders as disks and some as slabs or planks. Slabs are shown in the right hand side of Fig. 1. For disks, the shock would propagate along the non-growth direction. For slabs, the initiating shock would propagate along the growth allowed direction.

Plate Impact Shock Initiation Experiments

Reduced density sample material for shock initiation experiments was very limited. Furthermore, the cylinders were only 25.4 mm in diameter. For both of these reasons, we could not do embedded gauge experiments which typically require samples 50.8 mm diameter by 23 mm thick.[7]. Furthermore, there was not enough material to generate Pop-plots for each material type. Therefore we decided on a side by side comparison format.

A schematic of the shock initiation experiment is shown in Fig. 2. An aluminum flyer-plate, mounted on the front of a two-stage gas-gun projectile, impacts an aluminum base-plate, driving a shock wave through the base-plate and into the PBX 9502 explosive. In the explosive, the shock accelerates as the chemical energy in the explosive is released. If the explosive sample is thick enough, the shock wave will build up into a full detonation. Particle or mass velocity is measured at the interface of the explosive and a Poly-Methyl-Meth-Acrylate (PMMA) window. Four explosive samples with nominal thicknesses of 3, 4, 5, and 6 mm are mounted on the aluminum base-plate, allowing us to observe the evolution of the reactive wave after it propagates through different explosive thicknesses. Impact tilt probes were used to measure shock breakout at four places on the back of the aluminum base-plate as well as at the back of the four explosive samples. This allowed us to measure

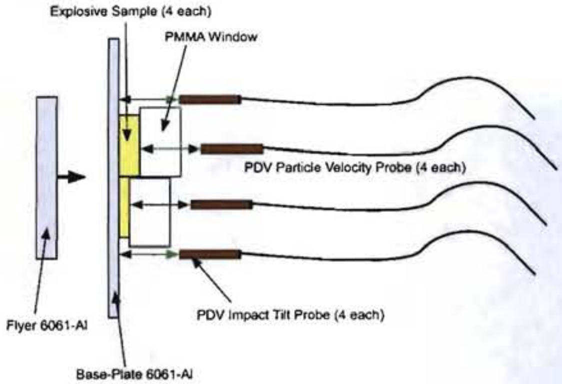

Fig. 2. Schematic of the plate impact shock initiation experiment.

project misalignment at impact (tilt) as well as the precise time the shock wave entered the explosive.

Figure 3 is a photo of the back of a target and shows how four explosive samples were mounted on the base-plate. A square corner was machined on each of the disk-cut samples to place most of each sample within the 50.4 mm diameter of the projectile. Samples were glued (Angstrom Bond ®epoxy) onto the aluminum base-plate with the corner in the center. Aluminum foil mirrors, (the silver dots seen in the photo of Figure 3) were glued onto each explosive sample at a radius of 12.7 mm from the base-plate center. Mirrors, 6 μm thick, reflect Doppler shifted light back into the PDV probes. PMMA windows (Rohm and Haas type II UVA plexiglass) were then glued on top of the explosives. Windows were in the form of blocks, and one window was glued on top of each explosive sample. Base-plate jump off or tilt measurements were at the in-cut region between disks. Figure 4 shows a complete target with PDV probes mounted. White lines are the fiber optics connecting to the probes.

The method we used for measuring the velocity of the explosive/window interface is known as Photon Doppler Velocimetry or PDV.[8] This is an optical interferometry technique using fiber optic components and detectors commonly used in the telecommunications field. We have successfully used PDV to measure wave profiles in detonating high explosives.[9] The 'probes' shown in Fig. 2 are simple lens systems which focus laser light from an optical fiber

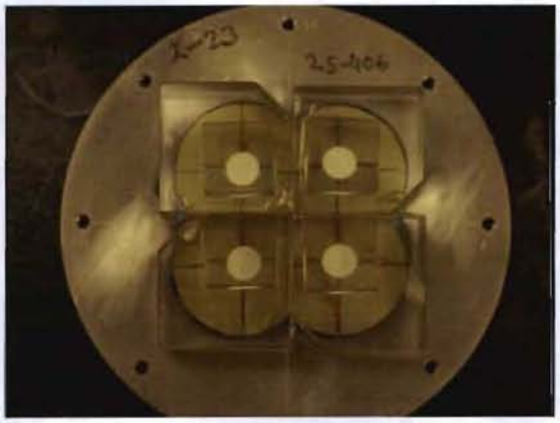

Fig. 3. Photograph of PBX 9502 samples and PMMA windows mounted on the aluminum base-plate. The back, non impact side, of the target is shown.

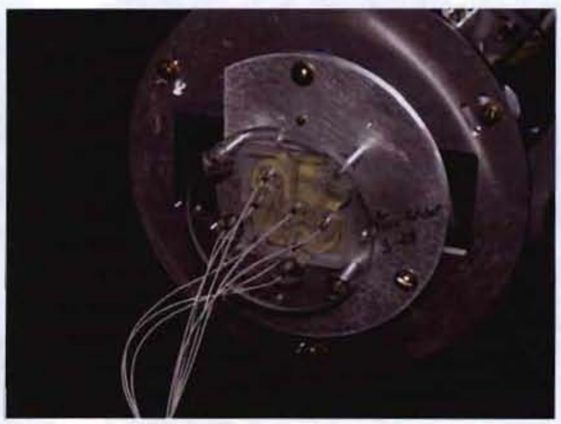

Fig. 4. Photograph of the back of a complete target mounted in the gas gun.

onto a spot and collect the reflected light which is Doppler shifted when the surface moves. Analysis of the Doppler shifted light allows determination of the surface velocity.[8]

The class of methods used to extract the surface velocity from PDV data are known as Time-Frequency-Analysis.[10] To analyze the experiments here, we used a Continuous Wavelet Transform and a wavelet developed by Harrop.[11] About 10 fringes or oscillations are included in the Full-Width-at-Half-Maximum of the wavelet envelope, and the rise time of analyzed waveforms is < 3 ns.

Results

Five successful experiments have been completed, and these are summarized in Table 3 below. The initial shock pressure in the explosive was calculated using the measured projectile impact velocity and the standard impedance matching technique.[12] Equation of state parameters used for the calculations are as follows: For 6061-T6 aluminum, ρ_0 =2.703 g/cm^3, $C_0 = 5.288$ km/s, and $S = 1.376$.[12] For PBX 9502 $C_0 = 2.938$ km/s, and $S = 1.77$. These are the nominal density values presented by Dick et al.[13] The measured density of the sample, listed in Table 3, was used. It is worth noting that, at the nominal density of 1.890 g/cm^3, the initial pressure in the shocked PBX 9502 would only be 0.6% higher for a fixed impact velocity.

Figure 5 shows wave profiles obtained in experiment 2s-405. This was the baseline material pressed to 1.870 g/cm^3 and not ratchet grown. Sample thicknesses associated with each wave profile are nominally 3, 4, 5, and 6 mm for all experiments with exact values listed in Table 3. These profiles are similar in character to those obtained with our embedded electromagnetic particle velocity gauges[7] and clearly show the buildup to detonation. The time origin (0.0 μ s) is the time at which the shock enters the sample(s). Times for all profiles have been corrected for the substantial 15.9 milli-radians of impact tilt. (The large impact tilts in these experiments may be due to an ill-designed projectile.) The sharp triangular profiles from the 5 and 6 mm thick samples indicate detonation, implying that the distance to detonation is between 4 and 5 mm for this experiment. The expected distance to detonation for PBX 9502 of nominal density (1.890 g/cm^3) is 5.3 mm. Thus, the pressed low samples result in greater shock sensitivity and therefore a reduced run distance to detonation.

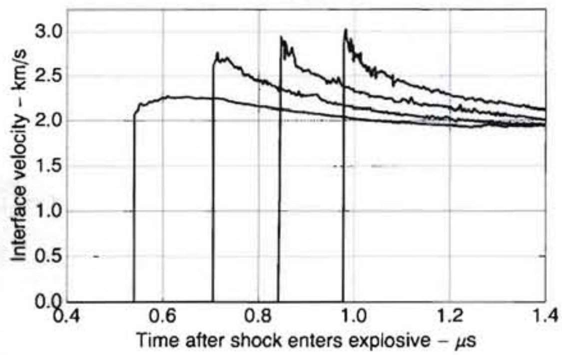

Fig. 5. Wave profiles from experiment 2s-405. PBX 9502 is not ratchet grown. Detonation begins between 4 and 5 mm

Because shot 2s-405 transitioned to detonation much faster than expected, we chose to reduce the impact velocity, and therefore the initial impact pressure on the remaining shots. For the side by side comparisons of response, the baseline is taken from shot 2s-440, a pressed low not ratchet grown charge. In other experiments we tried to duplicate the projectile impact velocity as closely as possible.

Figure 6 compares profiles from the pressed low material (solid lines) with profiles from the ratchet grown/no-load samples(dot-dash lines). In the discussion that follows, we will use the height of the wave front and the wave arrival times as measures of reactivity in the sample. More reactive samples will have waves with larger amplitude and which arrive sooner. With these criteria in mind, it is evident that both samples have very similar sensitivity. In both experiments, the transition to detonation is complete by 5 mm. The first and second profiles, however, show ever so slightly more reactivity in the pressed low samples.

Figure 7 compares profiles from the pressed low material (solid lines) with those obtained from PBX 9502 ratchet grown while under 100 psi axial load and cut into disks (dotted lines). It is evident that the pressed low material (solid lines) is quite a bit more sensitive: transition to detonation is at least 1 mm earlier, all waves arrive earlier, and all amplitudes are higher. This difference, however, could be a simple density effect because the samples which

Table 3. Summary of plate impact experiments on ratchet grown PBX 9502.

Shot# (key)	Charge ID/description	Density (g/cm^3)	Impact Velocity (km/s)	Initial Pressure in Explosive (GPa)	Sample thickness (mm)	Tilt (milli-radians)
2s-405 (solid)	Charge #3-28 pressed low baseline	1.870	2.222	14.35	3.027 4.027 5.038 6.011	15.9
2s-440 (solid)	Charge #3-30 pressed low baseline	1.870	2.139	13.62	2.855 4.011 5.033 5.958	9.7
2s-406 (dotdash)	Charge #2-23 pressed high ratchet grown no load	1.870	2.137	13.62	3.018 4.028 5.015 6.011	9.3
2s-412 (dotted)	Charge #4-03 pressed high ratchet grown 100 psi axial load (disks)	1.876	2.138	13.65	3.021 4.008 5.012 6.018	11.1
2s-413 (dashed)	Charge #4-16 pressed high ratchet grown 100 psi axial load (slabs)	1.876	2.138	13.65	3.021 3.990 5.012 5.987	11.0

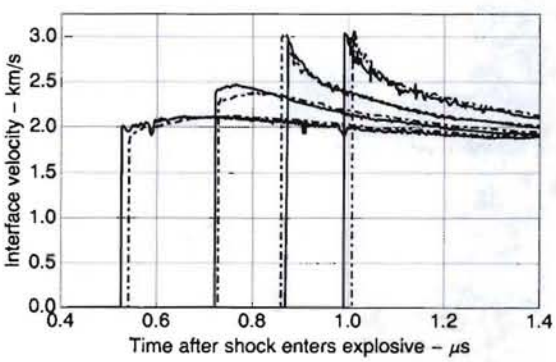

Fig. 6. Wave profiles from shot 2s-440, pressed low material (solid lines) compared with wave profiles from shot 2s-406, ratchet grown/ no-load (dot-dashed lines).

are ratchet grown under axial load are more dense by 0.006 g/cm^3. The increased density could be the cause of the lower shock sensitivity.

Figure 8 compares profiles from the pressed low PBX 9502 (solid lines) with those obtained from axially loaded ratchet grown 9502 which was cut in slabs (dashed lines). Again, it is evident that the pressed low material (solid lines) is more sensitive. Again, the difference, could be a density effect because the samples which were ratchet are more dense by 0.006 g/cm^3. The increased density of the ratchet grown samples could be the cause of the lower shock sensitivity.

Figure 9 compares profiles from PBX 9502 ratchet grown under axially load and cut into disks (dotted lines) or slabs (dashed lines). It was considered that these experiments might possibly uncover anisotropic behavior in the initiation response as the shock was directed along the direction of growth (slabs, dashed lines) or across the direction of growth (disks, dotted lines). As can be seen in Figure 9, there is no detectable anisotropy in the

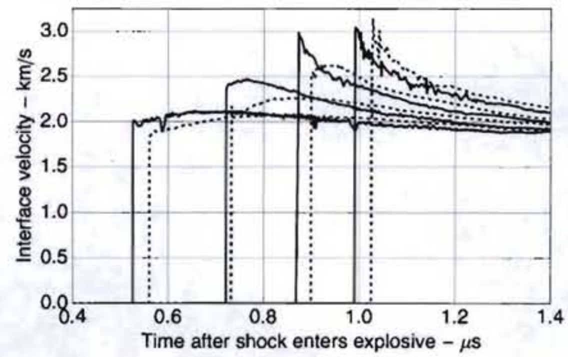

Fig. 7. Wave profiles from shot 2s-440, pressed low material (solid lines) compared with wave profiles from shot 2s-412, ratchet grown under axial load, disk cut (dotted lines).

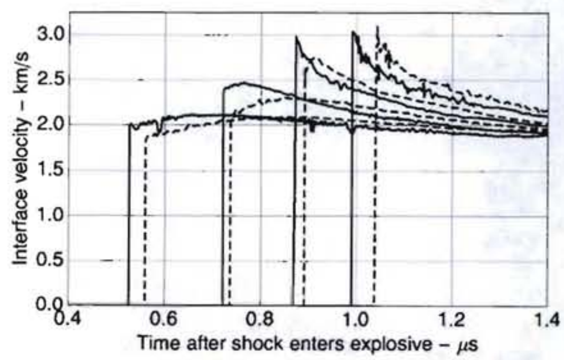

Fig. 8. Wave profiles from shot 2s-440, pressed low PBX 9502 (solid lines) compared with wave profiles from shot 2s-413, ratchet grown under axial load, slabs (dashed lines).

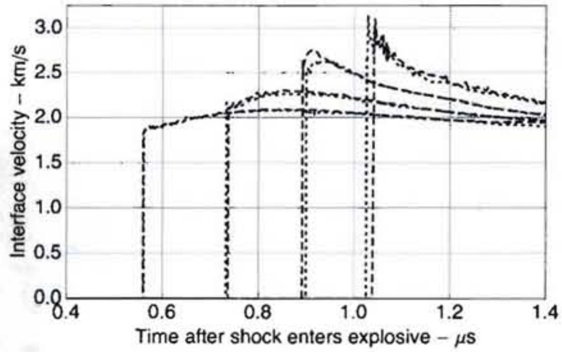

Fig. 9. Wave profiles from shot 2s-412, ratchet grown, axial load/disks (dotted lines) compared with wave profiles from shot 2s-413, ratchet grown, axial load, slab cut (dashed lines).

initiation response. Samples from both orientations initiate exactly the same.

Summary

These experiments reinforce several things about shock initiation of pressed explosives. For a fixed composition, shock sensitivity is most strongly dependent on the explosive's density, or more specifically, the volume percentage of void. More void results in greater shock sensitivity. All reduced density samples, that is all materials tested as part of this study, are more shock sensitive than nominal density PBX 9502.

The shock sensitivity ordering is as follows: nominal density PBX 9502 (1.890 g/cm^3) is the least sensitive. Axially constrained ratchet grown PBX 9502 (1.876 g/cm^3) is the next least sensitive, whether cut along (slabs) or across (disks) the axis. Unconstrained ratchet grown PBX 9502 (1.870 g/cm^3) is the second most sensitive. The pressed low material (1.870 g/cm^3) was very slightly more sensitive than the unconstrained ratchet grown material.

The pressed low PBX 9502 has larger pores than material pressed to nominal density and then ratchet grown.[5] For the long shock inputs in these experiments, larger pores in the pressed low material appear to be slightly more effective at generating reaction than the smaller pores in the ratchet grown material. This is likely a function of the amplitude and time dependence of the pressure pulse. Salyer found detonations to propagate in smaller diameters of ratchet grown PBX 9502 than in pressed low PBX 9502.[6] Of course, the pressure profile in a (failing) detonation wave is much different than the long shock inputs used in our experiments.

The ratchet growth in the axially constrained samples is clearly anisotropic. However, there is no clear evidence for anisotropy in the wave propagation or the shock initiation. From this result can we conclude that the void distribution or orientation anisotropic, or would shock wave propagation and shock initiation be sensitive to these anisotropies?

Ideally, one would like to measure initiation across a larger range of input pressures and for greater sample thicknesses. This was not possible in this study because of limited sample quantities. The side by side comparison of waveprofiles in otherwise identical samples which had received different treatments was a compromise.

Acknowledgments

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