Taylor impact tests on PBX composites: imaging and analysis

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Taylor impact tests on PBX composites: imaging and analysis

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Abstract. A series of Taylor impact tests were performed on three plastic bonded explosive (PBX) formulations: PBX 9501, PBXN-9 and HPP (propellant). The first two formulations are HMX-based, and all three have been characterized quasi-statically in tension and compression. The Taylor impact tests use a 500 psi gas gun to launch PBX projectiles (approximately 30 grams, 16 mm diameter, 76 mm long), velocities as high as 215 m/s, at a steel anvil. Tests were performed remotely and no sign of ignition/reaction have been observed to date. High-speed imaging was used to capture the impact of the specimen onto anvil surface. Side-view contour images have been analyzed using dynamic stress equations from the literature, and additionally, front-view images have been used to estimate a tensile strain failure criterion for initial specimen fracture. Post-test sieve analysis of specimen debris correlates fragmentation with projectile velocity, and these data show interesting differences between composites. Along with other quasi-static and dynamic measurements, Taylor impact images and fragmentation data provide a useful metric for the calibration or evaluation of intermediate-rate model predictions of PBX constitutive response and failure/fragmentation. Intermediate-rate tests involving other impact configurations are being considered.

1. Introduction

Previous applications of Taylor impact testing to PBX composites [1-3] were intended to provide mechanical response of these materials in the dynamic regime for constitutive model development and validation. To this end, high-speed cameras have been used to provide side-view contour images of PBX specimens during impact (at velocities 60 to 210 m/s) onto another PBX specimen [1] or a steel anvil [2-3]. PBX contours have been modeled/analyzed using: approximations to Taylor’s original theory [1], the dual-domain material point method [2], and ViscoSCRAM/ABAQUS [3]. As a complement to these studies, we have obtained high-speed images upon impact from two perspectives: the side-view contours, but also top-view. The latter images show radial crack formation very soon after impact for the PBX formulations of interest, insight which has significant implications for modeling efforts of the side-view contours (where cracks are not evident).

Because high explosive mechanical insult can result in violent reaction (HEVR), a variety of configurations have been designed and studied over the years to probe the mechanisms and threshold conditions responsible for ignition and reactive growth in these materials. Impact tests using PBX specimens as projectiles in a semi-confined state have been shown to result in HEVR at threshold conditions [4]. It is reasonable, therefore, to expect that at high enough velocity, our Taylor impact configuration may result in HEVR. Impact tests with HE projectiles have been modeled using a
cohesive finite element approach [5] and predictions have been made about critical velocities for ignition. These modeling efforts appear poised for calibration via post-impact analysis of the PBX fragment distribution.

Taylor impact tests have been performed on three different PBX-like formulations over a wide range of PBX projectile velocities. Impact image analysis and post-impact fragment-size analysis data have been collected and can be used to inform models relevant to HE fracture and the fragmentation that precedes HEVR in this impact configuration.

2. Experiment and Results

Two of the three formulations studied are HMX-based. PBX 9501 is 95% by weight (wt%) HMX, 2.5 wt% Estane (polyester-polyurethane) and 2.5 wt% nitroplasticizer (NP). PBXN-9 contains 92 wt% HMX with 2.0 wt% binder and 6.0 wt% plasticizer. Finally, HPP, a non-HMX propellant, contains 69 wt% ammonium perchlorate, a 19 wt% mixture of Al and Fe, and 12 wt% polyurethane binder. The contrast of these formulations with their fragmentation response is valuable. PBX 9501 is formulated using a 3:1 ratio of class 1 to class 2 HMX crystals. PBXN-9 is formulated using a 6:5 ratio of class 1 to class 5 HMX crystals, and this formulation has a softer binder which is more highly plasticized than PBX 9501. The mechanical response of these PBXs has been characterized by us previously as a function of temperature and strain rate in quasi-static uniaxial compression and tension (data not shown). Specimens are ~76 mm long and 16 mm diameter. For velocities ranging from 60 to 210 m/s, no evidence of HEVR was observed.

The gas gun design used in PBX Taylor impact tests has been shown previously [3]. A composite-lined barrel is used, no sabot. In addition to mounting a port camera for side-view images of the projectile impact, we replaced the steel lid of the boom box with a Lexan lid and used a top/front-mounted mirror with a camera to the rear of the box facing the barrel. This allowed us to obtain ~45° top-front images during impact, as shown in figure 1.

![Figure 1](https://example.com/image1.png)

**Figure 1.** Front/top images of PBX 9501 impact at 85 m/s at approximately (left to right): 25 µs before impact, 100 µs after impact, and 225 µs after impact.

Such images allowed us to measure/estimate the hoop-strain at which fractures opened in the PBX projectile. Figure 2a shows digitized outlines as HPP impacts the anvil at 84 m/s. Cracks became visible in frame 4. From these images, 16 µs/frame, we estimate a strain rate of 1e 4 s⁻¹ and that failure occurs at a tensile strain of 38%. Figure 2b shows this failure strain on a time-temperature shifted master-curve of tensile failure strains from quasi-static tests (shifted to 23°C equivalence). For the other PBXs studied, cracks were observed at frame 1, consistent with their more brittle nature as observed in quasi-static tests.

After each impact test, the boom box was swept and PBX fragments/debris collected. Sieve analysis provided the fragment size distribution for each test. In figure 3a, comparative sieve results are shown for each formulation with projectile velocities around 200 m/s. The two HMX formulations have similar fragment-size distributions that are quite consistent with the size distribution of HMX.
crystals put into the formulation, while the HPP fragment-size distribution is very different (we were not able to learn the solids particle-size distribution for the HPP formulation for the purpose of comparison). In all impact tests, the tail end of the specimen remained intact and was the largest surviving fragment, and figure 3b shows the inverse correlation of its mass with test velocity for each material. For all impact velocities, HPP gives the largest tail fragment, with PBX 9501 and PBXN-9 being quite similar. Figure 3c shows the relative wt% recovered for each test. Higher velocities tend to have lower percent recovery as the very smallest particles are made airborne and escape the vessel (airborne dust is visible on the remote camera immediately after high-velocity shots). This effect is stronger for more brittle materials, as the total recovered wt% in the high-velocity range is highest for HPP, then PBXN-9, and lowest for PBX 9501.

For the two HMX-based composites, a simple fragmentation model is proposed. The HMX particle-size distribution that was used in making the formulation is assumed to be the basis for the fragmentation pattern observed on impact. Using the initial relative weight distribution of the HMX crystals, the very smallest particles (<1 micron) are combined with the proper wt% of binder to produce a “dirty binder” for each formulation. A calculation is then made in which the remaining HMX crystals are coated with this dirty binder, and their new sizes and weights are estimated to determine the particle size distribution. For each impact velocity, the weight of the intact tail fragment is accounted for as the weight distributions are calculated.

In figure 4, we plot the measured post-impact fragment-size distributions for (a) PBX 9501 and (b) PBXN-9 at six velocities (solid lines and filled symbols). Data are provided in table 1 and 2. Overlayed (dotted lines and open symbols) in figure 4 are the calculated particle size distributions.
using the initial HMX particle sizes in the formulation, after coating the larger crystals with dirty binder. In the calculated distributions, the effect of velocity is to vary the size of the large ontact tail fragment; this keeps the relative particle distribution the same for each impact velocity, but as the velocity goes up, so does the magnitude of the distribution (i.e. number of particles).

3. Results and Discussion

Overall, there is remarkable consistency in the fragmentation results of this study when one considers the crudeness of the process (sweeping debris from a boom box). Ideally, we would have data in figure 4 for higher and higher impact velocities until some threshold, where an HEVR initiation/reaction was observed. These data would then be the basis for understanding how mechanical energy is dissipated and/or converted to thermal energy towards initiation. Unfortunately, the limitations of our gun did not allow us to achieve velocities above ~210 m/s with these projectiles, and no signs of HEVR were observed. Despite this, the fragmentation results may be of great utility in laying the groundwork for modelling PBX impact and the conditions which lead to ignition.

Figure 4. (left) PBX 9501 and (right) PBXN-9; measured post-impact fragment size distribution (closed symbols, solid lines) overlayed with fragment size distribution calculated from initial HMX in formulation (see text).

Table 1. PBXN-9 particle size distribution at each impact velocity (numbers are wt%).

| sieve size (microns) | 96 m/s | 120 m/s | 136 m/s | 163 m/s | 185 m/s | 202 m/s |
|----------------------|--------|---------|---------|---------|---------|---------|
| 8000                 | 57.44  | 38.44   | 31.28   | 20.76   | 19.26   | 6.17    |
| 4750                 | 2.64   | 1.08    | 0       | 0       | 0       | 6.96    |
| 2360                 | 17.52  | 16.57   | 9.58    | 3.66    | 1.10    | 0.87    |
| 1400                 | 5.74   | 10.47   | 10.93   | 9.76    | 7.34    | 4.74    |
| 1000                 | 3.37   | 6.50    | 7.32    | 8.33    | 9.78    | 7.65    |
| 710                  | 2.75   | 6.10    | 7.64    | 10.16   | 11.42   | 9.76    |
| 500                  | 2.04   | 5.57    | 8.40    | 11.41   | 12.72   | 13.83   |
| 355                  | 1.80   | 4.13    | 6.20    | 8.36    | 10.00   | 11.95   |
| 250                  | 1.59   | 4.04    | 6.40    | 9.33    | 9.98    | 12.98   |
| 180                  | 0.68   | 1.43    | 0.39    | 3.15    | 3.38    | 4.27    |
| 125                  | 0.92   | 2.45    | 4.09    | 5.86    | 5.48    | 8.06    |
| 90                   | 0.47   | 1.36    | 2.40    | 3.55    | 3.55    | 5.02    |
| 63                   | 0.40   | 1.08    | 2.07    | 3.93    | 3.79    | 4.66    |
| 45                   | 0.017  | 0.28    | 0.68    | 0.66    | 1.10    | 1.91    |
| 1                    | 0.016  | 0.21    | 0.30    | 0.63    | 0.87    | 0.98    |
Table 2. PBX 9501 particle size distribution at each impact velocity (numbers are wt%).

| sieve size (micron) | 89 m/s | 114 m/s | 125 m/s | 132 m/s | 165 m/s | 209 m/s |
|---------------------|--------|---------|---------|---------|---------|---------|
| 8000                | 64.67  | 61.81   | 58.85   | 57.39   | 48.13   | 40.48   |
| 4750                | 3.09   | 0       | 0.01    | 2.64    | 4.80    | 1.57    |
| 2360                | 7.18   | 4.65    | 3.23    | 1.97    | 2.23    | 3.52    |
| 1400                | 3.90   | 4.52    | 3.24    | 3.26    | 3.36    | 3.26    |
| 1000                | 3.11   | 4.12    | 3.87    | 3.31    | 4.26    | 3.33    |
| 710                 | 2.94   | 5.19    | 5.80    | 4.74    | 5.78    | 5.02    |
| 500                 | 2.60   | 5.54    | 6.56    | 5.65    | 6.85    | 7.13    |
| 355                 | 1.90   | 4.24    | 5.54    | 5.38    | 6.21    | 7.43    |
| 250                 | 1.44   | 4.03    | 5.41    | 5.71    | 6.83    | 9.19    |
| 180                 | 0.60   | 1.47    | 1.61    | 2.32    | 2.24    | 4.46    |
| 125                 | 0.61   | 1.82    | 2.40    | 3.25    | 3.80    | 6.41    |
| 90                  | 0.25   | 0.48    | 1.03    | 1.37    | 1.87    | 2.97    |
| 63                  | 0.25   | 0.76    | 1.02    | 1.31    | 1.50    | 2.05    |
| 45                  | 0.07   | 0.19    | 0.13    | 0.24    | 0.26    | 1.08    |
| 1                   | 0.10   | 0.52    | 0.80    | 0.89    | 1.04    | 1.59    |

The calculated particle-size distributions in figure 4, based on our very simple model, consistently overestimate the number of particles that were measured at each velocity. This may be due to the small particulates that are lost and experimentally unaccounted for in the measured distribution. However, the calculation and simple fragmentation model described above do capture the general bimodal shape and the trend with impact velocity. Because the overall shape of the experimentally-measured distribution does not change with impact velocity, we conclude that fragmentation primarily occurs between HMX crystals and not through them. It may be that under confined conditions, fragmentation patterns would be quite different.

4. Conclusions

Using two camera positions, we have shown that for the HMX-based PBX composites of interest, even at the lowest impact velocities, radial cracks appear within the first frame (16 to 25 μs). For HPP, radial cracks opened after a few frames and estimates of strain at failure were made which agreed with master-curve information from quasi-static tension testing of HPP. Any effort to model the dynamic response as captured by side-view contours must take into account the early failure and fracture of the material where volume and density are not conserved.

For our current specimen geometry, no sign of HEVR has been observed, and we are investigating other geometries that may enhance initiation mechanisms in the velocity range of our gun.

We have observed fragmentation patterns that are consistent with measured ductility of the binders and with the measured particle-size distribution of solids in the formulation. The very simple fragmentation model proposed for the HMX-based formulations assumes that fragmentation occurs consistent with the HMX particle-size distribution used in making the formulation. This simple model is sufficient to capture the bimodal distribution of the post-impact fragments, indicating that at least to a first approximation and under these unconfined conditions, fragmentation occurs primarily between HMX crystals and not through them. It is certain that other, more-sophisticated criteria for fragmentation could be proposed [5] and that these specimen impacts could be more-properly modeled towards gaining a better understanding of the energy dissipation and localization of heating, factors that play a role in the development of HEVR.
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