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RUNAWAY REACTION IN A SOLID EXPLOSIVE CONTAINING A SINGLE CRACK

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Abstract. Deflagrations were propagated into 80-μm-wide slots in PBX 9501 intended to simulate a small crack in the explosive. Two different slot lengths were tested: 4.06 cm and 19.1 cm. In the 4.06-cm-long slots, flame speeds ranged from 50 to 200 m/s and peak pressures ranged from 40 to 150 bar. In some cases, recovered explosive exhibited the formation of channels on the burning surface that were attributed to the reaction zone accessing defects in the explosive. Tests with the 19.1-cm-long slots exhibited much more violent reactions. Flame speeds up to 10 km/s were observed in the longer slots and accompanied by pressures as high as 1 kbar, causing the confining walls of the test cell to fail. Streak records and pressure data suggest the onset of combustion bootstrapping, a process where pressure buildup due to confined product gases is thought to allow the reaction zone to access continually smaller voids in the pressed explosive. This process can generate extremely high pressures that are not typically observed in a deflagrating explosive.

INTRODUCTION

Recent work[1] has determined that mechanically damaged high explosive (HE) is capable of generating combustion pressures and flame speeds dramatically in excess of those observed in undamaged HE. Specifically, samples of PBX 9501 subjected to mechanical impact and/or thermal stresses developed crack systems with widths ranging from 2 μm to 200 μm.[1] These cracks increase the surface area available to a flame and promote more rapid energy release during combustion.

In an HE undergoing conductive burning, experiments have demonstrated that the flame will penetrate cracks large enough to support the reaction zone, increasing the surface area of the flame and the rate of gas production. For geometries with sufficient confinement, the increased gas production elevates the pressure in the crack and reduces the reaction zone thickness, allowing the flame to enter smaller-width cracks and possibly create additional fractures.[2] It has been deduced[3] that as the reaction zone thickness decreases sufficiently to enter the smallest of cracks, the flame surface area will grow appreciably and rapidly pressurize the HE. Under high enough pressures, it may even be possible for the flame to access the porosity between the HE grains and cracks created in the HE crystals during the pressing process, substantially increasing the surface area available to the flame.

This runaway of pressure and burning area, termed combustion bootstrapping,[3] can accelerate the combustion mode from conductive burning to convective burning or compaction-initiated combustion and, in the most extreme cases, may result in deflagration-to-detonation transition (DDT).[2] Thus, an understanding of the critical pressure at which the reaction will enter a specific crack size is a critical component in predicting the onset of violent reaction in mechanically damaged HE.

In this work, we present an experimental study of the transition from conductive burning to violent reaction in PBX 9501 containing a single slot intended to simulate a small crack. For simplicity and to allow detailed study of the combustion bootstrapping process, our experiments model only a single crack rather than the network of cracks that is more common in mechanically damaged HE.[1] Prior to this work, direct observation of that transition process has proved elusive as it occurs over a period of a few microseconds, at micron-sized length scales, and does not appear to be connected to any observable feature. This study has significant safety implications as it demonstrates that mechanically damaged HE at room temperature is capable of violent reaction or possible DDT in response to a deflagrative ignition source.

PREVIOUS WORK

In 1970, Godai[4] first noted the existence of a critical pressure, below which a reaction could not enter a crack of a specific width in a propellant. He was unable to formulate a relationship describing this critical pressure as a function of the crack and propellant parameters, but Belyaev[5] did in 1973. In Belyaev's equation, the critical pressure at which the reaction zone would enter a crack was a function of the crack width w and two HE-dependent parameters

$$P^{1+2n} w^2 = const \qquad (1)$$

that are calculated from experimental observations. When properly calibrated the equation agrees well with experimental data.

Work by Berghout et al.,[6] has determined the parameters n and $const$ for PBX 9501 to be 0.92 and 8×10^8 kg^{3}m^{-1}s^{-6} respectively. They have used these results to infer the size of the connected porosity in mechanically damaged samples of PBX 9501.[1]

Dickson et al.[2] observed the significance of cracks in the onset of violent reaction in thermally damaged HE. High-speed photography recorded the formation and spreading of cracks in heated PBX 9501 following ignition of a deflagration. The freshly opened crack surfaces appeared to be ignited promptly, allowing the deflagration to rapidly propagate throughout the sample. In one case, DDT was also observed following self-ignition of the explosive during heating.

More recent work by Berghout et al.[7] examined flame propagation in 80-μm-wide slots in PBX 9501 that were confined on all sides but one, which exhausted into a blowdown chamber. The effect of slot lengths (4.06 and 19.1 cm) on the flame spread was investigated. Flame speeds were measured with a framing camera with a maximum framing rate of 62,500 fps and pressures were measured with piezoelectric transducers. For the shorter length slots, flame speeds of 30-60 m/s were observed with maximum pressures of 140 bar. During these tests, the flame oscillated in and out of the slot at frequencies of approximately 1 kHz for approximately 10 ms before extinguishing.

Two tests[7] were performed with the longer length slots as well. During the first test, the reaction entered the slot and burned in a steady manner for tens of milliseconds before extinguishing. A second test was assembled identically to the first, with the only difference that the bolts of the confining cell were preloaded to a higher value to ensure that the cell was properly sealed. Upon ignition, the reaction rapidly propagated through the narrow slot reaching a flame speed of at least 1500 m/s. Pressures in the center of the slot reached 7 kbar within a few hundred microseconds, destroying the test cell. The contrast in the level of reaction violence between the two long slot tests was startling and was the motivation for the current work.

Hill[3] proposed that the violent reaction in the second long slot test of Berghout et al.[7] was due to a mechanism he termed combustion bootstrapping, which was described above.

EXPERIMENTAL DETAILS

In the current study, experimental parameters were kept as close as possible to those of Berghout et al.[7] in order to recreate their violent reaction. The framing camera in their study was replaced by a streak camera in order to obtain higher resolution measurements of the flame position and velocity. The streak camera was focused on the slot between two pieces of PBX 9501. Assuming that the flame motion in the narrow slot was one dimensional, the streak record provided the position of the flame in the slot versus time. The streak camera was better able to accommodate the large range of speeds observed[7] in these experiments and provided a continuous record of flame position data versus time, compared to the dozen or so available from the framing camera.

Deflagrations were initiated with an electrically heated wire. Thus, the amount of time required for initiation to occur varied on the order of tens of milliseconds. A continuous-access streak camera was used to capture the flame entrance into the slot and light was cut off from the camera at the end of the experiment to prevent overwriting of the film. The specifics of each test cell are given below and are followed by a description of the experimental procedure.

Short Slot

Each short slot was created by spacing apart two PBX 9501 tablets of dimensions 4.06 cm × 1.02 cm × 0.254 cm with 80-μm-thick cellophane tape. Tape strips that were 1.6 mm wide were placed along the 4.06-cm-long edges on one face of one of the HE tablets. The other HE tablet was then placed on top of the tape strips, creating an 80 μm × 0.703 cm × 4.06 cm gap bordered on the top and bottom by the HE and on the sides by the tape.
This HE-tape assembly was then inserted into the steel test cell as shown in Fig. 1. When assembled, the cell confined the HE-tape assembly on all sides except one, where the channel exhausted into an ignition chamber that was 2.29 cc in volume. Optical access of combustion chemiluminescence in the slot was provided by a 6.35-mm-thick acrylic window that was mounted flush with the HE-tape interface along one side of the slot. The steel wall opposite the window contained four pressure transducer ports located at the HE-tape interface. One port (P1) was located in the ignition chamber and ports P2, P3, and P4 were located 0.508 cm, 2.03 cm, and 3.56 cm, respectively, from the unconfined face of the HE-tape assembly. All piezoelectric transducers used in the short slot tests were model PCB 113A23. Prior to insertion into the test cell, all faces of the HE-tape assembly except the unconfined face were lightly coated with vacuum grease or RTV to seal the interface between the HE and the test cell walls.

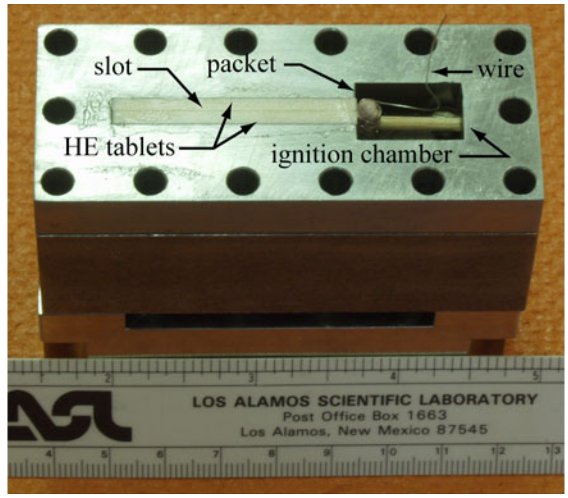

FIGURE 1. The short slot test cell with the window removed.

A packet located in the ignition chamber consisted of a 2.54 cm × 3.18 cm piece of cigarette rolling paper wrapped around 100 mg of stoichiometric DHT (3,6-dihydrazino-s-tetrazine) and ammonium perchlorate (NH_4ClO_4) mixture. A length of 30 AWG nickel-chromium (nichrome) wire was wrapped around this packet. The ignition packet and wire were pressed against the exposed face of the HE using a small wooden stick as shown in Fig. 1.

The steel test cell consisted of 3 pieces: the middle section containing the HE and ignition chamber, the back section containing the pressure transducers and the front section containing the acrylic window. Sealing between each section was accomplished with 0.13-mm-thick clear Teflon gasket material. The assembled short slot test cell with the acrylic window in place is shown in Fig. 2.

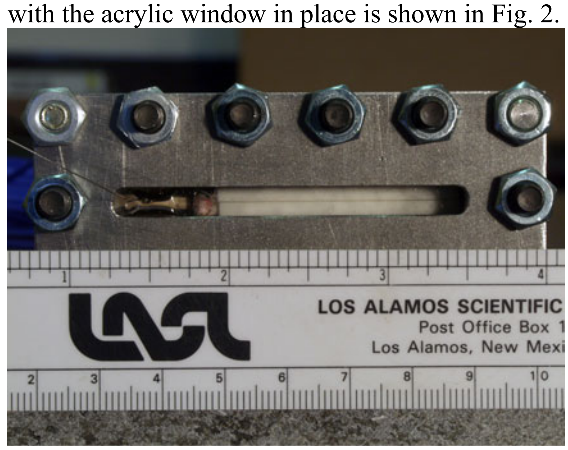

FIGURE 2. The assembled short slot test cell.

Long Slot

The long slot cell design was similar to that of the short slot test cell. Two tablets of PBX 9501 with dimensions 19.1 cm × 1.27 cm × 2.54 cm were spaced apart using a 1.6-mm-wide and 80-µm-thick strip of cellophane tape placed along the 19.01-cm-long edges of one face of one of the HE tablets. Placing the other HE tablet on top of the tape created a channel between the HE pieces that was 19.1 cm × 0.953 cm × 80 µm. Each HE tablet was glued to a 19.1 cm × 1.27 cm × 1.27 cm piece of brass to prevent breakage of the HE during handling. The HE-tape assembly was then inserted into the test cell.

The long slot test cell consisted of two steel pieces and a 2.54-cm-thick acrylic window (Fig. 3). The back steel piece contained pressure transducers and the HE assembly, while the front steel piece contained the window. The test cell confined the HE tablets on all sides except one, which exhausted into a 10.23 cc ignition chamber. Pressure transducer ports P2, P3, and P4 were aligned with the slot in the back piece and were located 1.0 cm, 7.0 cm, and 13.0 cm, respectively, from the unconfined end of the HE. One transducer (P5) was located at the closed end of the HE assembly (19.0 cm from the unconfined end) and another (P1) was located in the ignition chamber. All piezoelectric transducers used in the long slot tests were model PCB 109A02 or 109B02.

The ignition chamber contained a packet containing between 450 and 500 mg of the DHT and ammonium perchlorate propellant mixture. As with the short slot tests, the packet was wrapped with a nichrome wire and pressed against the exposed face of the HE. During assembly, 0.13-mm-thick clear Teflon gasket material was located between the HE assembly and the top and bottom portions of the test cell.

Operation

Prior to initiation of combustion in the flame cell, a Cordin 136 continuous access streak camera was spun up to speed with the shutter open. Light from the test cell window was guided to the camera via a planar first surface mirror.

Reaction was initiated in the flame cell by running current through the wire wrapped around the propellant packet. Heating of the wire ignited the HE, the propellant and pressurized the cell above 10 bar, which is the critical pressure for an 80-µm slot according to Belyaev's equation for PBX 9501.

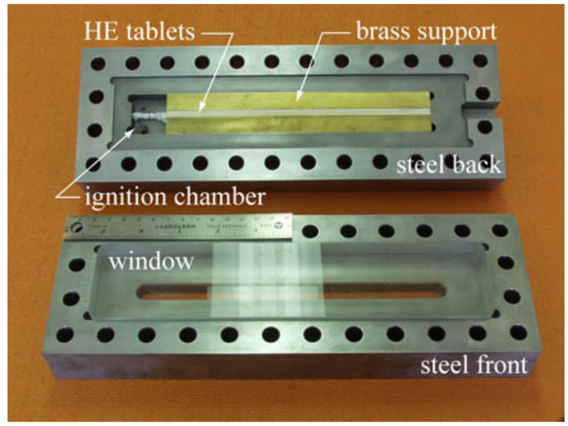

FIGURE 3. The disassembled long slot test cell.

Pressurization of the pressure transducer P2 served as a trigger signal for the data acquisition system and also for a pulsed laser that placed a series of timing dashes on the streak film. Trigger values ranged from 10 to 100 bar depending on the particular experiment.

To prevent overwriting of the streak record due to the continuous access nature of the streak camera, an SE-1 detonator glued to the back of the planar mirror was timed to fire and shatter the mirror several milliseconds after the trigger signal. Destruction of the mirror cut off light to the camera. Under the slowest stable rotation rate, the camera was able to provide 14 ms of streak data, while the data acquisition system provided up to 120 ms of pressure data sampled at 1 MHz.

SHORT SLOT RESULTS

A streak image and set of pressure traces from a short slot test is shown in Fig. 4. The vertical axis is time, which increases down the page. The horizontal axis is both distance across the 4.06-cm-long slot and pressure. The baseline of each pressure trace corresponds to the location of the transducer that obtained it. Pressure increases to the right. Fiducial marks from the pulsed laser are located at the rightmost part of the streak image. Each dash length corresponds to 100 µs in time. The reference time of zero corresponds to where the first transducer inside the slot measured 10 bar. At this pressure, the laser pulse began writing fiducial marks on the film.

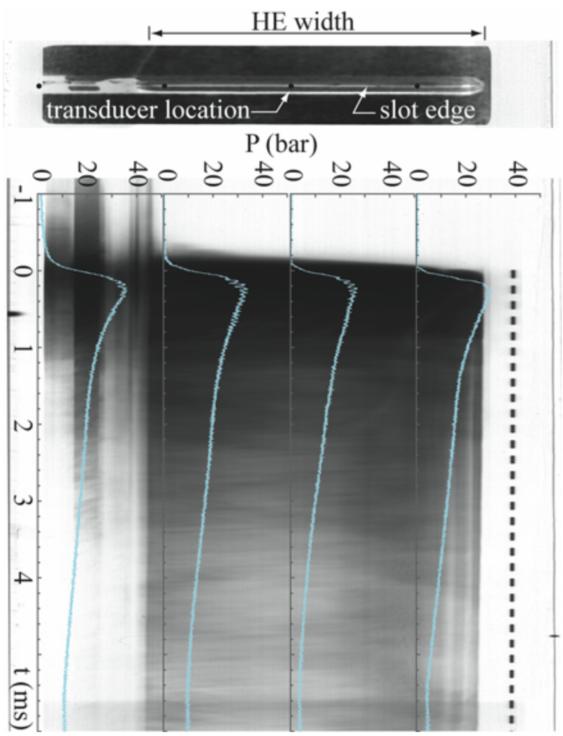

FIGURE 4. Short slot streak and pressure data. The orientation of the slot is shown in the top still image.

During the experiment, the nichrome wire takes several milliseconds to heat up before the propellant packet ignites. Ignition of the packet can been seen in the upper left corner of the streak trace at about -0.5 ms. The packet appears to burn intensely for approximately 1 ms. (The streak trace shown is a negative image, so darker exposures correspond to brighter light output.) Shortly after the packet ignites the pressure at the first transducer location (5.08 mm inside the slot) increases to 10 bar, triggering the laser fiducial.

The flame enters the slot at a velocity of about 100 m/s, but rapidly accelerates and propagates throughout most of the slot at approximately 200 m/s. Only in the last 10% of the slot does the propagation velocity decrease as the flame approaches the wall.

A pressure wave due to the product gases from the deflagration building up in the channel travels behind the flame front. Typically the maximum pressures measured in the short slot tests ranged from 40 to 150 bar and the flame velocity ranged from 50 to 200 m/s. The pressure wave always lags behind the flame front and travels at velocities on the order of 350 m/s, which is close to the initial sound speed of the air in the channel.

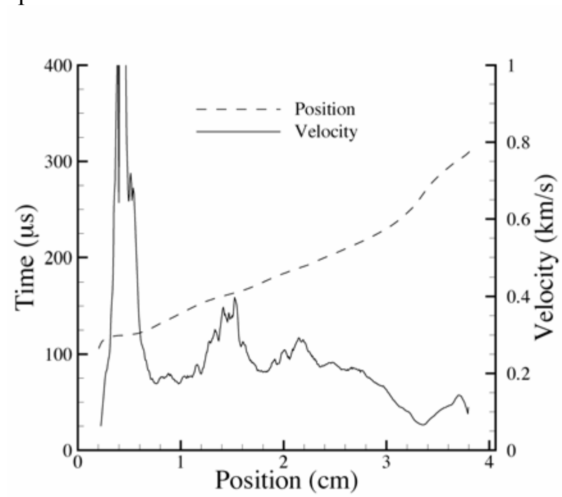

FIGURE 5. Flame position and velocity data from Fig. 4.

Flame position and velocity data from an edge-detection program that identifies the onset of chemiluminescence in the slot for the data in Fig. 4 are shown in Fig. 5. In the case of the data shown, the leading edge of the flame was assumed to occur at 80% of the darkest pixel present in the image. The position data were smoothed using boxcar averaging over 10% of the position axis. Velocity data were obtained by differentiating the smoothed position data. The calculated velocity was then smoothed using the boxcar routine again averaging over 1% of the position axis. The result shows the unsteadiness of the flame propagation in the narrow slot.

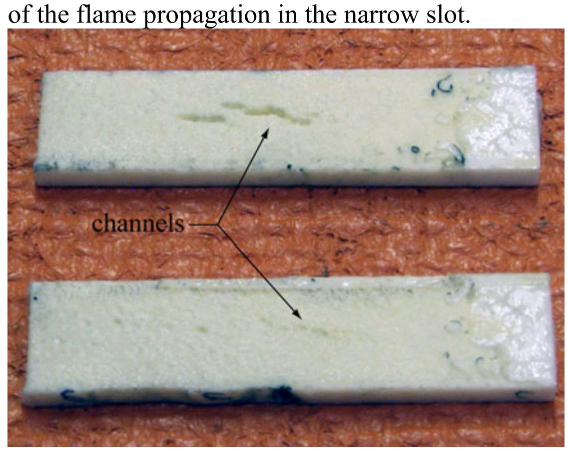

FIGURE 6. Channels on the burning surface.

In all tests, the reaction in the short slot test cell would quench after burning for approximately 30 ms. Disassembly of the test cell revealed that the gasket material failed, allowing product gas to escape from the cell. This rapid depressurization resulted in quenching of the reaction in the cell.

Removal of the remaining HE from the test cell after quenching revealed that the slot had enlarged during the test. Typically, post-test slot widths were found to have enlarged to 635 μm (compared to the initial slot width of 80 μm). Some HE tablets had channels that appeared to have been carved out of the surface that was exposed to the flame. In some cases, the channels only penetrated the surface of the tablet a small amount, as shown in Fig. 6. In other cases, the channels penetrated the entire tablet, as shown in Fig. 7. When channeling occurred, it was always present on both tablets. Furthermore, the location of the channels on each pair of tablets was well aligned. This indicates that the reaction was able to preferentially penetrate certain regions of the HE tablets, possibly due to the presence of a defect in the material that was not observed at the time of assembly. The alignment of the channeling in both pieces of HE hints that penetration of the flame into a defect created a locally high pressure that allowed the reaction to better penetrate the surface of the HE tablet opposite to the defect.

LONG SLOT RESULTS

Violent reactions were observed to occur in half of the four long slot tests performed. The violent reaction destroyed the test cell and shattered the explosive before quenching occurred. A streak image from a long slot experiment ignited with 500 mg of propellant in the ignition packet is shown in Fig. 8. The image format is identical to the short slot data presented above in Fig. 4. Fiducial marks from the pulsed laser are located at the left of the streak image and, as before, each dash denotes 100 μs of time. Light from the hot nichrome wire and the burning propellant can be seen in the upper left corner of the image. The flame then enters the slot, decays in velocity somewhat in the middle of the slot and then rapidly accelerates as it propagates through the final section of the slot. Roughly 100 μs after the flame has entered the slot, the magnitude of chemiluminescence emitted from the slot becomes much brighter at several different locations along the slot. This brighter mode of burning then spreads throughout the entire slot.

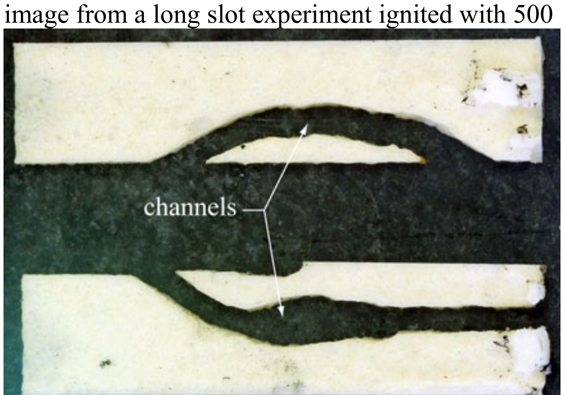

FIGURE 7. Channels penetrating the HE.

Smoothed flame position and velocity data of the flame entrance into the slot are shown in Fig. 9. These data were obtained with the edge-detection program, which smoothed the position data over 9% and the velocity data over 2% of the position axis.

Flame propagation in the early portion of the slot is similar to that observed in the short slot tests. For the first four centimeters of the slot, the velocity is approximately 200 m/s. Then the flame rapidly accelerates to 1000 m/s until it reaches the middle of the slot (10 cm), where its velocity briefly decays to 500 m/s before fluctuating between 2000 and 10,000 m/s for the final portion of the slot.

The onset of the regions of increased chemiluminescence can be interpreted in several ways. It is possible that the Teflon gasket between the window and the HE failed, allowing the reaction to enter the space between the HE and the window. A second possibility is that, as the pressure increases in the slot, new chemical reactions that are significantly more luminous became dominant. A final possibility is that as the pressure rises, the reaction is able to penetrate pores or cracks created by the high pressure in the slot. The increased burning area then emits more light into the slot, possibility also transmitting through the translucent HE.

It is difficult to definitively identify the cause of the increased luminosity. Gasket failure cannot be confirmed as the subsequent destruction of the test cell destroyed the gasket. It is also not possible to confirm the occurrence of reaction zone penetration into cracks or defects in the violent tests since the HE was severely damaged. All three possibilities could have been present in each test.

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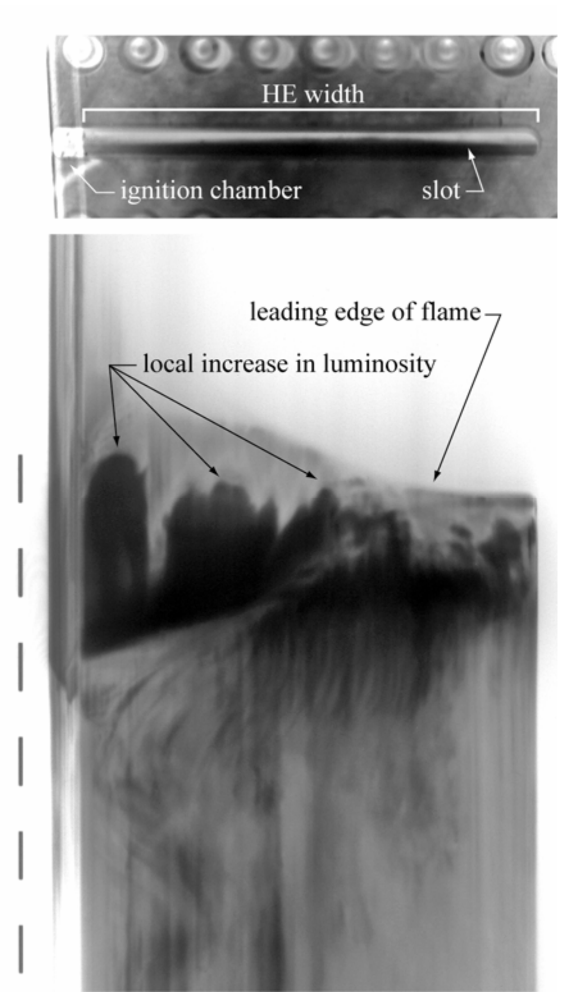

FIGURE 8. Streak data from a long slot test.

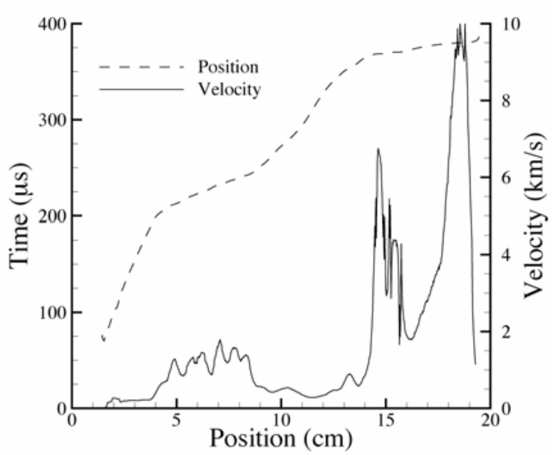

FIGURE 9. Flame position and velocity data from Fig. 8.

Pressure data (Fig. 10) from a similar test, which differed from that of Fig. 8 only in that 50 mg of the propellant was removed from the ignition packet and spread though the first half of the slot, are shown in Fig. 10. During that test, the pressure in the long slot rose to 1 kbar over a period of about 100 μs. The decrease in pressure after the slot was pressurized to 1 kbar is attributed to failure of the confining walls of the test cell. Note that during pressurization of the slot to 1 kbar, the pressure in the ignition chamber only rose to 0.2 kbar. This indicates that the cell did not fail due to the uniform and quasi-static pressurization of product gas throughout the cell, but due to a dynamic event that caused the slot to pressurize more rapidly than the ignition chamber.

The locally high pressure in the slot suggests the onset of combustion bootstrapping[3] in the narrow slot. Product gases from the deflagration are produced faster than they can escape into the ignition chamber, causing a pressure runaway in the slot. It is possible that, at a critical pressure, the reaction is able to penetrate into pores or cracks created by the high pressure in the HE, and this is evidenced in the streak record (Fig. 8) as the localized bright regions.

Belyaev's equation may be used to estimate the penetration of the porosity by the reaction zone by employing a technique similar to that used by Berghout et al.[1] With the previously mentioned constants for PBX 9501, Belyaev's equation predicts that the reaction zone will penetrate 85 μm gaps at 10 bar, 3.3 μm gaps at 100 bar and 0.12 μm gaps at 1 kbar.

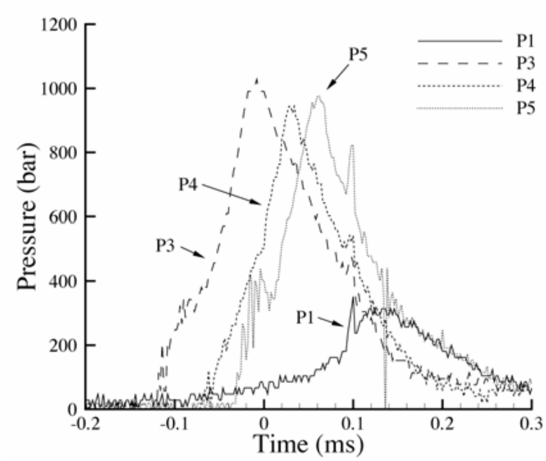

FIGURE 10. Pressure data from a long slot test.

Berghout et al.[1] contains a high magnification view of a pristine PBX 9501 sample. The HMX grains in the sample contain cracks that appear roughly 4 μm wide, while the spacing between HMX grains is on the order of 10 μm. Ideally those spaces are filled with binder, but in practice the binder does not evenly penetrate all gaps between the grains. Additionally, machining of the explosive (as was done to the tablets in this study) can create additional fissures as grains are knocked loose. Thus, it seems likely that the reaction zone was able to access the HE porosity at the high pressures observed in the slot.

Note that the above values may be inaccurate as the maximum pressure used to calibrate the constants was 18 bar,[6] which is well below the 100 to 1000 bar range of pressures observed in the long slot experiments. Furthermore, Belyaev's equation may not even be valid at the high pressures and small length scales discussed.

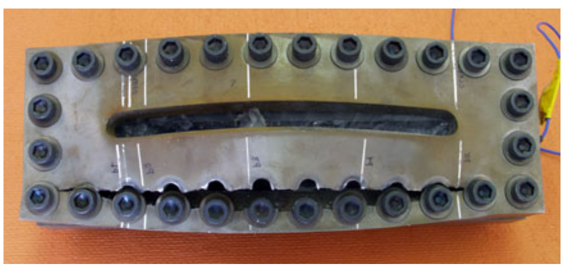

FIGURE 11. A destroyed long slot test cell.

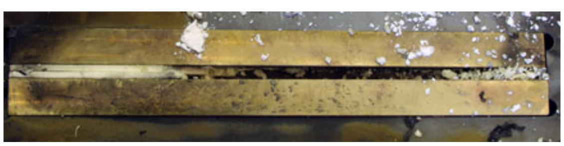

FIGURE 12. Shattered explosive from the long slot test of Fig. 8. The ignition chamber is located to the left of the image.

After approximately 100-200 μs of burning, failure of the test cell results in depressurization of the slot and the fading of the intense luminosity in the streak record.

An image of the destroyed long slot cell is shown in Fig. 11. The steel used to construct this cell was not hardened and thus failed at a lower pressure (1 kbar instead of 7 kbar) and ruptured more plastically than earlier experiments[7] which used hardened steel. The shattered explosive remaining after the test is shown in Fig. 12. The lack of HE remaining in the center of the slot and the extensive damage of the HE at the closed end agree well with the pressure data of Fig. 10. Dramatically less damage occurred near the open end of the slot, where lower pressures were measured.

FIGURE 13. Recovered explosive from a non-violent long slot test prior to removal from the test cell.

FIGURE 14. Streak data from a non-violent long slot test.

In other long slot experiments, violent reaction was not observed and the HE reacted in similar fashion to the short slot tests, pressurizing the slot to between 200-300 bar and burning for 10-20 ms before depressurization and quenching occurred. Recovered explosive (Fig. 13) from these non-violent tests exhibited far less damage than occurred in the violent cases. Streak data from a non-violent long slot test is shown in Fig. 14. As with the violent reactions, regions of localized luminosity are apparent, although each region does not appear to merge with adjacent regions, as occurred in the violent reaction of Fig. 8. Analysis of recovered explosive from the non-violent tests is underway in an effort to determine the cause of the increased luminosity. Although not confirmed, it is thought that failure of the gasket early in experiment prevented rapid slot pressurization and the onset of violent reaction.

CONCLUSIONS

Deflagrations were propagated into 80-μm-wide slots of two different lengths in PBX 9501 to determine the effect of slot length on reaction violence. The slots were intended to simulate cracks in the explosive. A streak camera was used to measure the flame position and speed in the slot versus time. Pressure transducers also measured the pressure in the slot.

In the shorter length, 4.06-cm-long slot, flame speeds between 50 and 200 m/s were observed. Maximum pressures in the slot ranged from 40 to 150 bar. After 30 ms, the flame in the slot was always observed to quench without consuming all of the PBX 9501 in the test cell. Flame quenching was attributed to depressurization of the slot due to gasket failure. The depressurization increased the reaction zone length of the flame such that it was no longer able to exist in the narrow slot.

Runaway reaction was observed to occur in the 19.1-cm long slot. Flames in the first 4 cm of the long slot propagated at similar velocities to those of the short slot tests, however, as the flame continued to propagate though the long slot, it accelerated to velocities ranging from 1000 m/s to 10,000 m/s. Pressures as high as 1 kbar were also measured in the longer length slots, which failed due to the high pressure. The streak record for the long slot tests showed the onset of a significantly brighter and localized burning mode about 100 μs after the flame first entered the slot. Some long slot tests did not react violently, instead burning in similar fashion to the shorter-length slots. Non-violent reactions in these cases were attributed to premature failure of the sealing gasket in the experiment, preventing pressurization of the slot.

While the data are not conclusive, the localized luminosity coupled with the high pressure in the slot suggest that the reaction was able to penetrate defects or pores in the HE, providing evidence of combustion bootstrapping.[3] Ongoing work, including the collection of temperature measurements is underway in order to further characterize the observed runaway process in narrow slots in PBX 9501.

ACKNOWLEDGEMENTS

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DISCUSSION

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Lawrence Livermore National Laboratory, CA

Good work. How did you select the slot width and length? Do you plan to measure gas flame temperature?

REPLY BY S.I. JACKSON

The slot width was chosen to be both large enough to allow the reaction zone to enter the slot when pressurized by the ignition packet and small enough to confine the product gas. Earlier work by Berghout et al.[6] provides estimates of the pressure at which the reaction will enter a slot of a particular width. Gas flame temperature measurements are ongoing and will be presented in future work.