LA-UR-99-3273

Approved for public release; distribution is unlimited.

Title:

MEASUREMENT OF CONVECTIVE BURN RATES IN GAPS OF PBX 9501

Author(s):

H. Laine Berghout, Steven F. Son, and Blaine W Asay

Submitted to:

http://lib-www.lanl.gov/cgi-bin/getfile?00796860.pdf

MEASUREMENT OF CONVECTIVE BURN RATES IN GAPS OF PBX 9501

H. Laine Berghout, Steven F. Son, and Blaine W Asay

Los Alamos National Laboratory, Los Alamos, NM 87545 USA

Abstract. Impact or thermal ignition of high explosives, HE, results in deformation that can lead to fracture. Fracture, combined with high pressure, dramatically increases the available surface area and changes the mode of combustion. Recent impact and cookoff experiments on PBX 9501, (HMX, octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine, with a binder), have shown complex cracking patterns caused by impact or pressurization. Fast reactive waves have been observed to propagate through the cracks at about 500 m/s. We present experiments that investigate the propagation of fast reactive waves in cracks of PBX 9501, focusing on the reactive wave velocity and on the interplay of pressure and crack size. Experiments at initial pressures of 6.0 MPa reveal nonoscillatory reactive wave propagation velocities around 7 m/s for a 100 µm slot. Similar experiments at lower pressure exhibit unstable reactive wave propagation in the slot with periodic oscillations whose frequencies vary with combustion vessel pressure. In threshold pressure experiments for combustion propagation into closed end slots of PBX 9501 we find that combustion propagates into 2 mm, 1 mm, and 100 µm slots at approximately 0.1, 0.2, and 0.9 MPa, respectively. This is the first known study that focuses on the effect of convective burning in voids of PBX 9501.

INTRODUCTION

The shift from conductive or normal burning to convective burning is a key step in the deflagration-to-detonation transition in explosives and other energetic materials. Conductive burning involves primarily conductive heat transfer from the gas-phase flame region to the surface. In contrast, convective burning involves heat transfer primarily by mass flow. The existence of defects where combustion can occur in an energetic material greatly increases the likelihood of convective burning. The effect of defects on combustion has major implications for the safety and reliability of energetic materials.

Voids and cracks in explosives may result from numerous environmental and physical factors. Impact, aging, and variations in temperature and pressure associated with combustion are a few of the factors that can produce defects. At sufficiently high pressures, these defects provide the necessary conditions to produce convective burning. There exist numerous studies on the effects of voids and cracks on combustion of some common propellants,(1,2) but relatively few studies exist of the effects of voids and cracks on combustion of high explosives.(1) Explosives such as HMX, (octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine), typically use a binder that makes it possible to shape and machine the explosive and that improves its strength. The binder affects the number, shape, and size of voids, as well as influences the kinetics of combustion. Our studies investigate the effects of voids and cracks on the combustion of PBX 9501, an HMX based explosive with a binder. In addition to improving our understanding of safety aspects related to PBX 9501, these experiments provide useful data for current efforts to develop detailed models of violent, explosive reactions.

Recent experiments highlight the importance of cracks and voids in the ignition, combustion, and detonation of PBX 9501. Idar et al. observe extensive cracking resulting from impact in samples of PBX 9501.(3) They find that damaged PBX 9501 has a lower impact threshold for violent reaction than pristine material. An example of their recent work is included in this volume. Figure 1 shows ignition initiated by the impact of a shearing projectile in a PBX 9501 disk. Ignition is seen to occur first in the cracks caused by the impact. The mechanically coupled cookoff

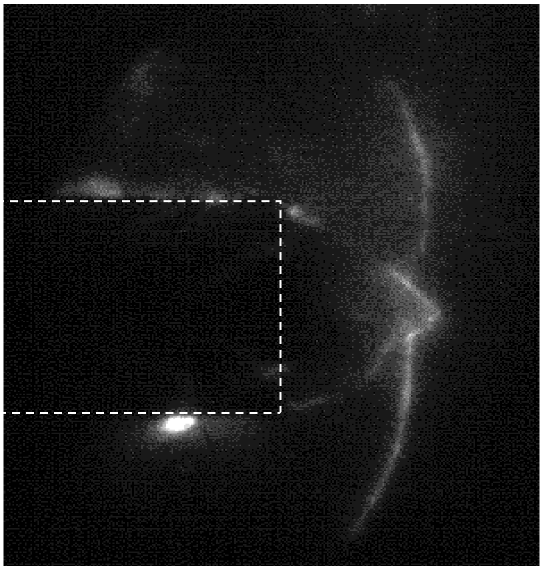

Figure 1. Ignition initiated by impact of shearing projectile in PBX 9501 from Henson et al.(4) The dashed box outlines the projectile that has impacted the sample from the left.

experiments of Dickson et al. slowly heat a confined sample of PBX 9501 to a well-defined temperature then ignite the sample. They detect ignition throughout intricate networks of cracks that are caused by heating and pressurization.(5) Figure 2 shows luminous reaction in cracks during a mechanically coupled cookoff experiment. The fast reactive waves propagate through the cracks at velocities on the order of 500 m/s.

Previous research on burning in voids and cracks of propellants has focussed on the factors that affect how the presence of such defects contributes to convective burning in propellants. The important variables include defect shape, dimension, and connectivity, inert gas pressure in the defect prior to ignition, and the change in the gas pressure during the experiment.

EXPERIMENTAL SETUP

The sample is composed of two 15.0x7.5x40.0 mm pieces of PBX 9501. One of the pieces is machined so that when the two pieces are combined they form an assembly of 15x15x40 mm with a flat slot 34.0 mm in length and of the desired width. A resistance-heated NiCr wire ignites one of the 15.0x15.0 mm faces while clear acrylic sheets on the remaining five faces inhibit burning along the sides and allow the slot to be viewed by visible imaging.

Figure 2. Luminous reaction in cracks of PBX 9501 during mechanically coupled cookoff experiment from Dickson et al.(5)

We conduct the experiments both open to ambient pressure and in a combustion vessel pressurized with Ar at up to 6.0 MPa. The pressure vessel is constructed of stainless steel with an internal volume of two liters and provides four optical access ports. A Conax Buffalo sealing gland provides electrical access for internal diagnostics.

We use several diagnostic tools to monitor the progression of reactions in the slot. A Canon XL-1 digital video system records the entire event at 30 frames per second. High-speed digital imaging is provided by Olympus Encore MAC-4000S, Kodak EKTAPRO HG 2000, and Kodak Motion Corder SR-500 video systems. An Omega Model PX605-10KGI pressure transducer monitors the pressure in the combustion vessel, which is recorded with Tektronix Model TDS 460A and TDS 540A digital oscilloscopes. Ionization pins inserted into the PBX 9501 slot provide a trigger signal for the video and pressure recording systems.

RESULTS AND DISCUSSION

Our experiments investigate the dependence of the flame propagation velocity on the initial pressure and determine the critical pressure for flame propagation into the slot. In both cases we use closed end slots in PBX 9501 with the slot at the initial pressure of the combustion vessel.
Figure 3 displays a sequence of high speed video images showing the progress of the luminous front into a 100 μm slot in PBX 9501 at 6.0 MPa. The deflagration begins on the right of the frame and propagates to the left. The inset indicates the relative timing of each frame. At this stage the

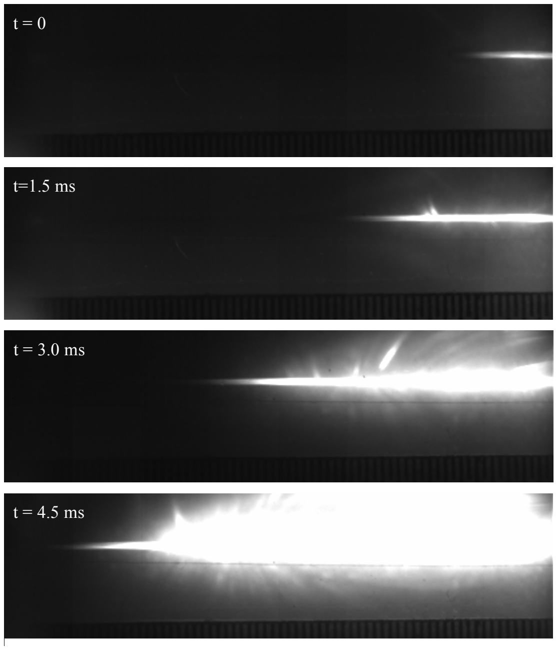

Figure 4. Sequence of high-speed video images showing the progresses of the luminous front into a 100 µm slot during deflagration of a sample of PBX 9501 at an initial pressure of 6.0 MPa. The slot can be seen lying horizontally through the middle of each frame with explosive flats above and below it.

material in the crack has not yet begun to regress significantly and the apparent widening of the crack is due to intense light scattering and the resulting saturation of the video signal.

Figure 4 contains plots of time and rate versus normalized position of the flame tip to emphasize the progress of the flame as it propagates into the slot. The lower plot shows the data with a fourth degree polynomial fit indicated by the line. The upper plot shows the analytical derivative of the fit and indicates the propagation rate. Upon entering the slot, the flame accelerates and reaches its maximum propagation rate of about 7 m/s two thirds of the way into the slot. The flame front then decelerates as it approaches the closed end of the slot. Kumar and Kuo observed similar behavior in manufactured slots of various ammonium perchlorate based propellants.(6)

Our most recent experiments using 100 µm slots conducted at initial pressures of 1.4 MPa and 3.4 MPa also reveal initial flame propagation velocities in the 5-10 m/s range but, unlike the higher pressure experiment, they show oscillatory instabilities in the propagation of the flame into the slot. Figure 5 is a plot of the average luminosity of

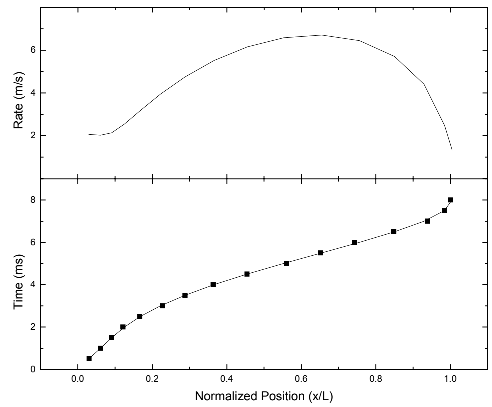

Figure 3. Plots of time and rate versus normalized position for the progress of the luminous front into a 100 µm slot during deflagration of a sample of PBX 9501 at an initial pressure of 6.0 MPa.

each frame of the high speed video record versus time. The average luminosity tracks the intensity of the light emitted from the crack and corresponds with the progress of the reaction in the slot. It is useful both at early times while the luminous front moves in and out of the slot as well as at later times when the slot is constantly illuminated but the intensity of the light continues to fluctuate. The luminous flame enters and exits the slot periodically with a frequency of about 400 Hz for the 1.4 MPa experiment and 800 Hz for the 3.4MPa experiment. This periodic flashing gradually gives way to steady burning in the slot as the pressure in the combustion vessel rises. This instability probably has the same origin as the L* instability common in small rocket motors.(7) The L* instability arises from coupling the energetic material's burn rate to pressure and is most common in configurations with a small value of the ratio L* of combustor cavity volume to nozzle throat area. Bradley and Boggs suggest that convective combustion instabilities could be important in the deflagration to detonation transition.(1) Further investigation is currently underway to understand these instabilities and their possible contribution to violent reaction in PBX 9501.

In addition to observing the velocity of the reactive wave as it penetrates the crack, we have carried out experiments to determine the critical pressure for flame propagation into slots of various widths. Flame enters 2 mm, 1 mm, and 100 µm

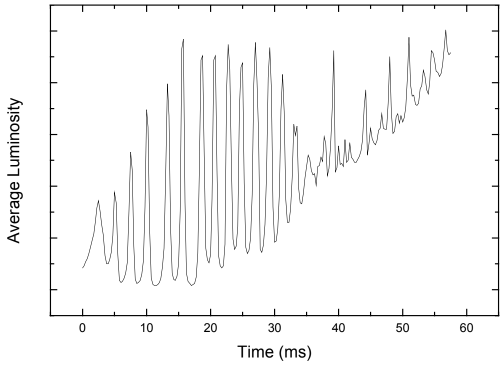

Figure 5. Plot of video frame average luminosity versus time for 100 µm slot in PBX 9501 at an initial pressure of 6.0 MPa.

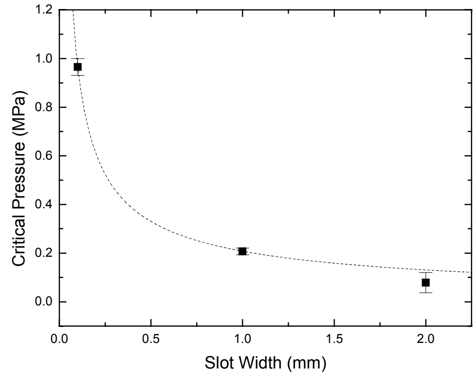

Figure 6. Plot of critical pressure vs. slot width.

slots at approximately 0.1, 0.2, and 0.9 MPa, respectively. The observed values are consistent with a simplified theoretical expression for a closed end slot(1)

$$p_*^{1+2n}\, w^2 = \text{constant}, \qquad (1)$$

where p_* is the pressure, n is the conductive burn rate pressure exponent and w is the slot width. The dashed line in Figure 6 results from Equation 1 where we have assumed n to equal one, the value for HMX, and the constant equal to 9×10^9 kg^3 m^{-1} s^{-6}. Continuing experiments in our laboratory are examining the threshold pressures for several other crack widths and the pressure dependence of the PBX 9501 burn rate.

CONCLUSION

We have observed combustion wave propagation in well characterized slots of PBX 9501, focussing on the interplay of pressure and slot width on the reaction wave velocity. At an initial pressure of 6.0 MPa, we observe nonoscillatory reactive wave propagation velocities of about 7 m/s in a 100 µm closed end slot. The same experiment conducted at lower initial pressures reveals unstable reactive wave propagation in the slot with periodic oscillations that are likely related to the L* instability common in small rocket engines. We have also investigated the threshold pressure for combustion propagation into slots of PBX 9501. Combustion propagates into 2 mm, 1 mm, and 100 µm slots at approximately 0.1, 0.2, and 0.9 MPa, respectively.

REFERENCES

1. H. H. Bradley and T. L. Boggs, Final Report Report No. NWC-TP-6007, 1978.
2. M. Kumar and K.K. Kuo, "Flame Spreading into Solid Propellant Cracks and Flaws," in *Fundamentals of Solid Propellant Combustion*, edited by Kou and Summerfield (AIAA, Inc, Ney York, 1984), Vol. 90, pp. 339-350.
3. D. J. Idar, J. W. Straight, M. A. Osborn *et al*., "Low Amplitude Impact of Damaged PBX 9501," in Shock Compression of Condensed Matter-1999, Snowbird, Utah, 1999.
4. B. F. Henson, B. W Asay, P. M. Dickson *et al*., "Measurement of Explosion Time as a Function of Impact Pressure," in 11th International Detonation Symposium, Snowmass, Colorado, 1998.
5. P. M. Dickson, B. W Asay, B. F. Henson *et al*., "Observation of the Behavior of Confined PBX 9501 Following Simulated Cookoff Ignition," in 11th International Detonation Symposium, Snowmass, Colorado, 1998.
6. M. Kumar and K. K. Kuo, AIAA Journal **19** (5), 610-618 (1981).
7. E. W. Price, "L* Instability," in *Nonsteady Burning and Combustion Stability of Solid Propellants*, edited by L. De Luca, E. W. Price, and M. Summerfield (AIAA, Inc, New York, 1992), Vol. 143, pp. 325-361.