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LLNL-TR-541891

Initiation and Detonation Physics on Millimeter Scales

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March 27, 2012

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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ABSTRACT

The LLNL Detonation Science Project has a major interest in understanding the physics of detonation on a millimeter scale. This report summarizes the rate stick experiment results of two high explosives. The GO/NO-GO threshold between varying diameters of ultra-fine TATB (ufTATB) and LX-16 were recorded on an electronic streak camera and analyzed. This report summarizes the failure diameters of rate sticks for ufTATB and LX-16. Failure diameter for the ufTATB explosive, with densities at 1.80 g/cc, begin at 2.34 mm (not maintaining detonation velocity over the entire length of the rate stick). ufTATB rate sticks at the larger 3.18 mm diameter maintain a constant detonation velocity over the complete length. The PETN based and LLNL developed explosive, LX-16, with densities at 1.7 g/cc, shows detonation failure between 0.318 mm and 0.365 mm. Additional tests would be required to narrow this failure diameter further. Many of the tested rate sticks were machined using a femtosecond laser focused into a firing tank – in case of accidental detonation.

Introduction

As demands increase for smaller, more versatile weapons systems, it is becoming vital to understand the physics of initiation and detonation of systems on a millimeter scale or smaller. Incorporation of micro electromechanical systems (MEMS) technology into fuzes will require drastically smaller high explosive (HE) components at the beginning of the initiation train. Simply scaling down from larger systems will not work at some dimension. It is necessary to understand this limit and the behavior of systems at and below this limit. The desire for more insensitive HE and lower threshold firing systems make this understanding even more vital. Important parameters to understand will be the *threshold of initiation*, the *failure diameter* of explosives used, the *run-to-detonation distance* of these explosives under various initiation conditions, the *effect of cracks and joints* and *crystal structure* in this small regime. These data need to be confirmed over a suitable range of operating temperatures.

LLNL has a tool that has proven extremely useful in creating test samples of small dimensions and geometric shapes necessary to carry out these tests [1]. LLNL has shown that the femtosecond laser is capable of safely cutting larger pressed samples of HE into desired shapes (in this case, ever smaller diameters – rate sticks) without altering the morphology of the cut surface. Leaving a pristine surface is very important in performing tests on these small samples since the smaller the HE sample, the more likely any surface variations might affect the outcome of the experiment. LLNL has shown there is no melting or other damage to the laser trimmed surface of the explosive. The laser could be used on deposited explosive films to form a desired architecture for initiation programmed detonation paths. An important advantage in making the samples this way is that larger, more uniformly pressed samples can be used to cut out the small samples of interest. This should provide much more uniform density of the samples as opposed to samples that are initially pressed to these small dimensions.

At LLNL, we have a demonstrated capability to carry out experiments to gather data on the important parameters listed above. We have high-speed streak cameras, digitizers and framing cameras, fast Fabry-Perot capabilities and optical set-ups to look at these small samples at appropriately high magnification.

With all the objectives, a major task is to properly produce the very small samples using the femtosecond laser. We have a good sense of how to do this for our current objectives and have successfully laser-cut many samples. The objectives also require the use of streak camera measurements of the breakout profiles of the tiny samples. Careful mounting of the samples, alignment and proper magnification are necessary to make these millimeter-scale explosive measurements.

Experimental

All of the rate stick experiment data in this report are captured on an electronic streak camera with relay lenses and notch filters designed to record 532nm (Figure 1). During each experiment, a custom designed, doubled Nd:YAG laser with a pulse width of approximately 4 µs is used to illuminate the side of each high explosive rate stick. Velocity data is retrieved by analyzing the shot film (with an optical 'comb' providing temporal resolution). The data signal on the film is generated by illuminating the side and end of the rate sticks with 532 nm laser light. The reflected light is then relay-imaged onto the streak camera photocathode. As the detonation wave travels up the rate stick, the reflection of the laser light from the high explosive disappears. Thus, when viewing shot film, the white area represents laser light reflecting off the high explosive. Whereas, darkness represents HE that has been consumed. The high voltage pulse-shaping network on the 532 nm Nd:YAG illumination laser was refurbished this past year and we now have a brighter, more dependable, light source to illuminate these mm-scale experiments.

Explosive Rate Stick Test Station

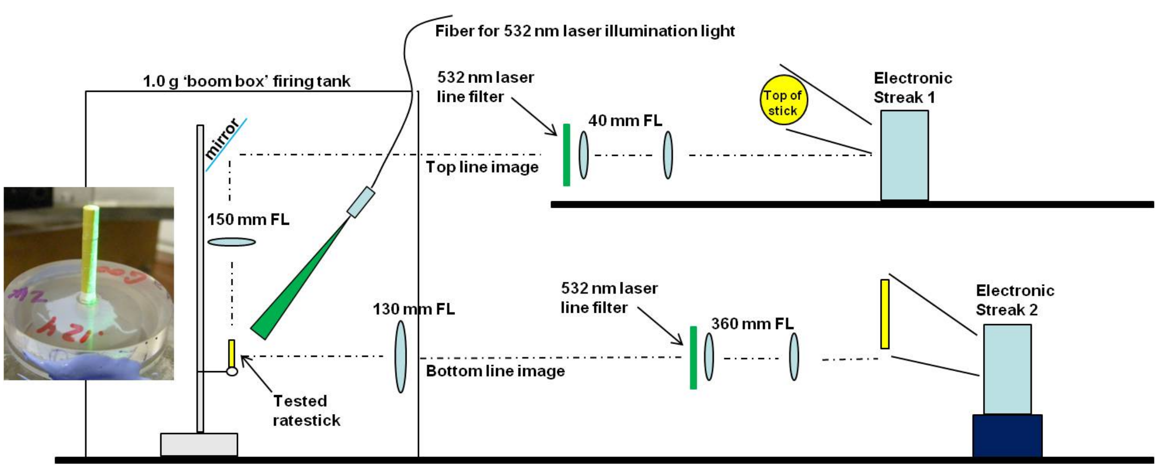


Figure 1.
Diagram of the system used to collect explosive rate stick data

For the rate stick measurements, 6.35 mm diameter, 10 mm long, samples of LX-16 were femtosecond laser-machined such that we had a 6.35 mm diameter base that was nominally 4.0 mm long and a "rate stick" section that was nominally 6.0 mm long and varied in diameter from 0.08 mm to 1.0 mm (Figure 2). A RP-2 detonator initiates the larger diameter section, called the pedestal, below the rate

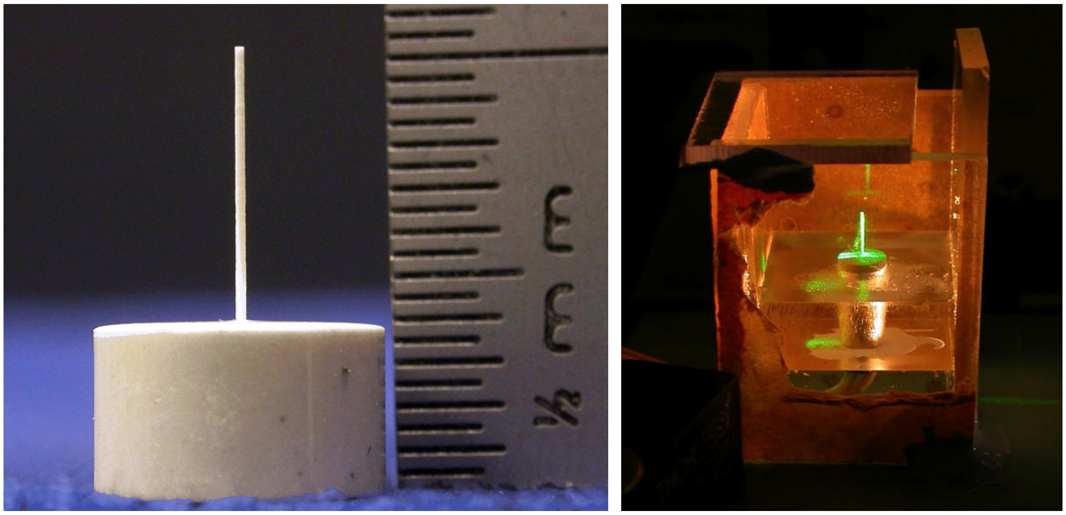


Figure 2.
190 µm diameter high explosive rate stick geometry (left). Laser illuminated rate stick (right) prior to test firing.

stick. Because ufTATB has a much larger failure diameter than LX-16, we made rate sticks of ufTATB by stacking miniature pellets of ufTATB on top of each other to give a long enough detonation run distance up the rate stick. The diagnostic configuration (laser and streak cameras) for the ufTATB and LX-16 rate stick tests is the same. Both explosives were 532nm laser illuminated for these experiments.

Results and Discussion

ufTATB rate stick experiments

While machining high explosives with the femtosecond laser works well, micro-machining explosives with this system is a costly and time-consuming process. Our experience with ufTATB indicates that failure diameters for rate sticks of this material would be significantly larger than rate stick parts we often experiment with. Because of the larger diameters involved, the ufTATB rate stick experiments were conducted by stacking and gluing mini-pellets of pressed ufTATB (Figure 3). Each completed rate stick maintained a minimum 6x1 (height vs. diameter) aspect ratio. This aspect ratio is similar to high explosive parts machined with our laser. In addition, to ensure each ufTATB rate stick began under full detonation, each stack also had an equivalent diameter PBX9407 (RDX based) initiating booster pellet. No attempt was made to produce these rate sticks from a single pressing because experience has shown us that we are unable to press HE pellets beyond a 2x1 aspect ratio without introduction of significant density gradients within the part – and this is especially problematic at smaller dimensions. These stacked rate sticks were then initiated with a commercial RP-2 detonator from the PBX9407 end. Figure 3 shows a stack-up of the 0.125” (3.18mm) ufTATB pellets. The green stripe seen on the right side of the column is the 532nm alignment laser illumination.

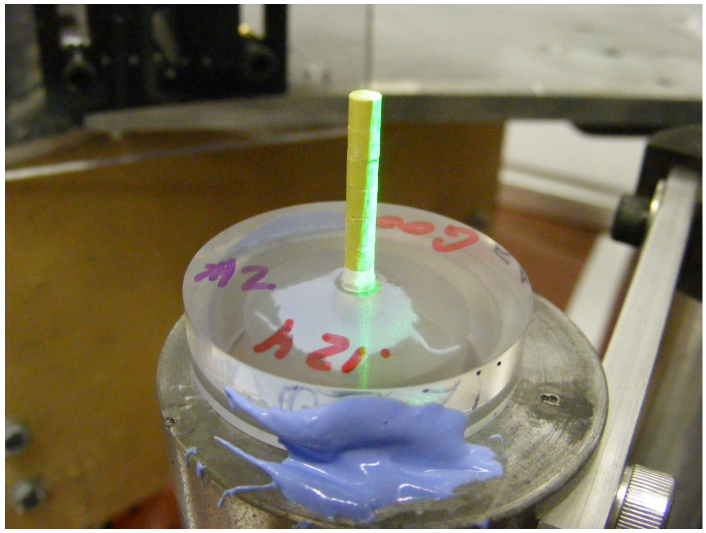


Figure 3.
0.125 inch (3.18 mm) diameter ufTATB pellets with the doubled Nd:YAG illumination laser shining against the stack. This was the smallest diameter tested where detonation maintained consistent speed up the entire length of the rate stick.

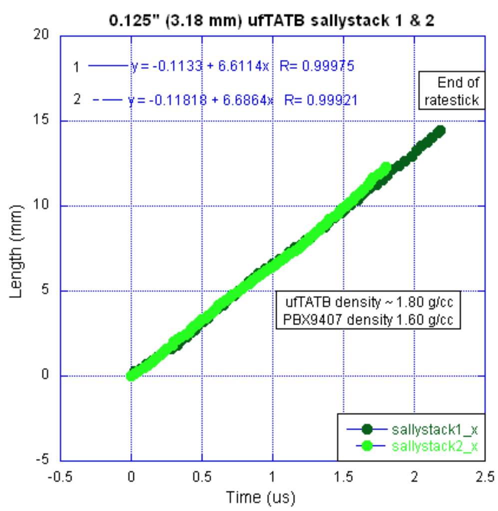


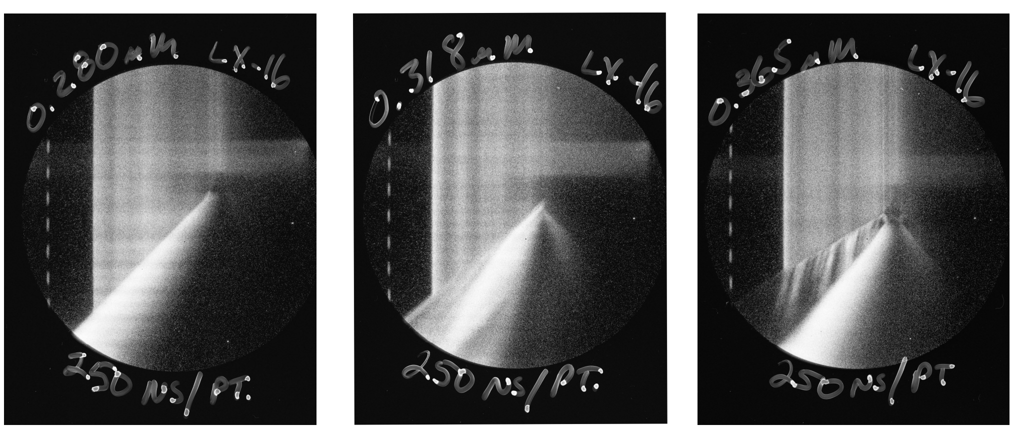
Figure 4.
This graph shows two 0.125” (3.18 mm) ufTATB rate stick shots. Both of these shots seem to indicate a sustained detonation velocity of approximately 6.65 mm/us over the entire length of the rate stick.

Figure 4 is the digitization of the raw film data and is the measured critical diameter for ufTATB. The smallest diameter that exhibited constant (albeit, somewhat reduced) detonation velocity was 0.125” (3.18mm). Smaller, 0.092” (2.34mm), diameter ufTATB showed detonation velocity in decline while traveling up the two tested rate-sticks. Table 1 shows data from additional shots with diameters both above and below these dimensions. Table 1 also shows that larger diameter ufTATB rate-sticks detonate at faster constant velocities. This faster, constant, detonation velocity seemed to peak when unconfined rate-stick diameters approached approximately 0.25” (6.35mm). Knowing the detonation velocity in these small scales is important in order to determine momentum and pressure from the velocity Hugoniot equation [2].

Diameter	Density	Velocity – no confinement
1 ea. 0.080” (2.03mm)	1.81	Unstable and deteriorating
2 ea. 0.092” (2.34mm)	~1.77	Unstable and deteriorating
2 ea. 0.125” (3.18mm)	1.80	6.61 mm/us 6.69 mm/us
2 ea. 0.200” (5.08mm)	1.80	7.09 mm/us 7.14 mm/us

Table 1.
Table shows the lowest 4 dimensions that were part of the experiment series. Constant detonation velocity could not be maintained with ufTATB on part diameters below 0.125” (3.18mm).

LX-16 rate stick experiments



0.280 mm diameter (failed to propagate) | **0.318 mm diameter (near failure)** | **0.365 mm diameter (successful detonation)**

Figure 5.
Three test-shots of LX-16 rate sticks showing the raw position vs. time data. These data are for 0.280 mm, 0.318 mm, and 0.365 mm diameter rate sticks. Timing marks on the left of each record are at 250ns intervals. The time direction is downward.

For the LX-16 rate-stick experiments (required smaller diameters), we returned to femtosecond laser machining 6mm diameter by 10 mm tall pellets pressed to 1.70 g/cc. The needed rate stick diameters with LX-16 are much smaller than ufTATB and, therefore, femtosecond machining was required. Raw data from the side-view camera (Figure 5) is shown for three diameters of rate sticks. The image on the far right of figure 5 shows detonation propagating to the end of the stick. By knowing the spatial and temporal calibration, we can find the slope of this distance versus time record and get the detonation velocity along the edge of the rate stick. As with ufTATB, with decreasing rate stick diameter, the detonation velocity falls off. This will continue in some manner until the detonation fails to propagate to the end of the rate stick.

Beginning with the LX-16 tests, we attempted a new method for controlling pedestal by-products (seen in the far left image of figure 5) from obscuring the detonation wave data traveling up the rate stick. Figure 6 shows our latest, simplified, version. Initially, the 4 mm tall base of LX-16 was set into position within the acrylic holder such that the top of this pedestal was depressed within the acrylic by 2 mm. This 2 mm depression – well – was then filled with photo-flo® treated water (allowing for ease of flow around the rate-stick). This method worked nicely. However, it reduced the visible portion of the rate-stick to be imaged onto the data-capturing streak camera by the depth of the water well. Because we wanted to maximize the length of the rate-stick seen by the streak camera, we tried the same test except with a 1 mm deep well of water over the pedestal and surrounding the rate stick. This 1 mm well seems sufficient to slow down the by-products from the pedestal while still recording the detonation wave. In Figure 7, any velocity data that is lower than 5 mm/μs is, in fact, the recorded velocity of the detonation products from the pedestal (including the water well) – *not* the LX-16 rate stick.

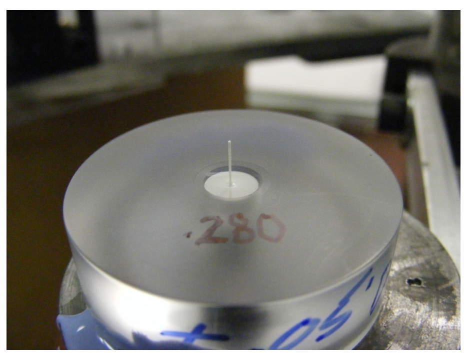
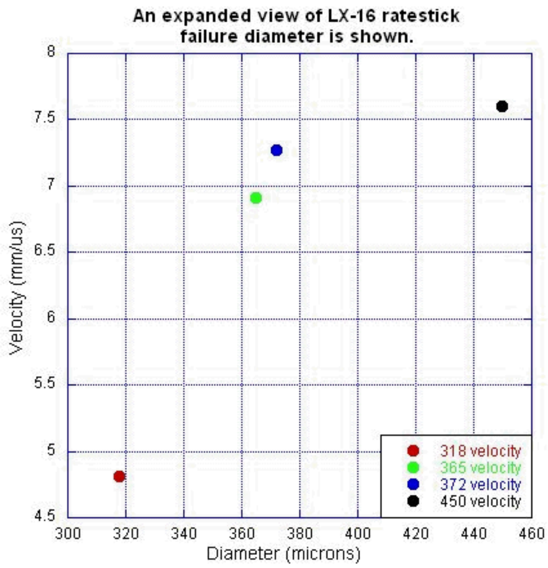


Figure 6.
0.280 mm LX-16, density at 1.701 g/cc with a 1 mm deep water well over the pedestal.

Laser machining LX-16 rate sticks with exactly specified rate stick diameters produced some technical challenges. With the limited number of rate-stick tests completed (and not damaged in process), we are able to establish critical diameter of LX-16 at between 0.318 mm and 0.365 mm (figure 7).



Diameter (mm)	Velocity (mm/us)
0.225	4.324*
0.260	4.755*
0.280	4.174*
0.318	4.816*
0.365	6.908
0.372	7.270
0.450	7.602
0.765	7.586
0.915	7.826
3.900	7.824
6.330	7.990

Figure 7.
The graph on the left indicates failure diameter for LX-16 to be somewhere between 0.318mm and 0.365mm. The table on the right shows all the LX-16 rate-stick shots. The two rows highlighted in red indicate the dimension where detonation extinguishes (0.318mm) in LX-16. Numbers followed by an asterisk indicate pedestal detonation product velocity – not actual LX-16 detonation velocity.

Summary and Conclusions

LLNL has successfully measured the detonation velocity of ufTATB rate-sticks made from stacking mini-pellets pressed to a density of approximately 1.8 g/cc. The ufTATB tests indicate failure in detonation at diameters of 0.092" (2.34mm). While, the larger 0.125" (3.18 mm) rate-sticks maintained a constant detonation velocity up the entire length of the rate-stick. Lastly, we've recently finished a preliminary series of tests on LX-16. These tests have indicated failure diameter for LX-16 to be between 0.318 mm and 0.365 mm. Additional measurements in the region of expected failure by refining our laser machining could be made to further narrow failure diameter for LX-16.

LLNL pioneered the use of femtosecond laser high explosive machining. This technology has been invaluable in our pursuit of ever smaller, precision-machined, HE parts of all sorts of shapes and dimensions.

Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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References

(1) Roeske, F.; Benterou, J. J.; May, C. A.; Phillips D. F.; "Initiation and Detonation Physics on a Millimeter Scale," *Munitions Technology Development Program, FY2006 Progress Report,* Lawrence Livermore National Laboratory, Livermore, CA, (2007).

(2) Cooper, P. W.; Kurowski, S R.; *Introduction to the Technology of Explosives*, p. 65, Wiley-VCH (1996)