Shock Initiation of an ε-CL-20-Estane Formulation

C. M. Tarver
R. L. Simpson
P. A. Urtiew

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SHOCK INITIATION OF AN ε-CL-20-ESTANE FORMULATION

C. M. Tarver, R. L. Simpson and P. A. Urtiew

Lawrence Livermore National Laboratory,
P.O. Box 808, L-282, Livermore, CA 94551

The shock sensitivity of a pressed solid explosive formulation, LX-19, containing 95.2% by weight epsilon phase 2,4,6,8,10,12-hexanitrohexaazaisowurtzitane (HNIW) and 4.8% Estane binder, was determined using the wedge test and embedded manganin pressure gauge techniques. This formulation was shown to be slightly more sensitive than LX-14, which contains 95.5% HMX and 4.5% Estane binder. The measured pressure histories for LX-19 were very similar to those obtained using several HMX-inert binder formulations. An Ignition and Growth reactive model for LX-19 was developed which differed from those for HMX-inert binder formulations only by a 25% higher hot spot growth rate.

INTRODUCTION

2,4,6,8,10,12-Hexanitrohexaazaisowurtzitane (HNIW) was first synthesized by Nielsen (1) and called CL-20. It has been shown that CL-20 has at least 5 different crystalline structures (2). In this paper, the epsilon phase of CL-20 is used with 4.8% by weight Estane binder to produce a formulation, LX-19 (formerly called RX-39-AB and RX-39-AC), that is an equivolume of binder analog of LX-14, which contains 95.5% HMX and 4.5% Estane. The shock sensitivity of LX-19 was measured at three shock pressures using the wedge test and the embedded manganin gauge techniques (3). One manganin gauge shot was fired using PBXC-19, a 95% ε-CL-20 in an ethyl vinyl acetate (EVA) binder formulation (4). This formulation has been tested by Wilson et al. (2) in the Modified Gap Test. An Ignition and Growth reactive flow model for LX-19 and PBXC-19 was developed, based on previous work on LX-14 and LX-10, which contains 94.5% HMX and 4.5% of the inert higher density binder Viton (5).

EXPERIMENTAL

The experimental geometry for the LX-19 wedge tests is shown in Fig. 1. The 100 mm smooth bore powder gun was used to fire 19 mm thick aluminum discs into 6.35 mm thick aluminum buffer plates on which 30 mm thick LX-19 wedges were mounted. Shock transit times through the explosive wedges were measured using 30 piezoelectric transducers positioned at a variety of precisely measured depths. The three aluminum flyer velocities were 0.3335 mm/μs, 0.5804 mm/μs, and 0.8004 mm/μs, producing initial shock pressures of 1.4 GPa, 2.7 GPa and 3.9 GPa, respectively, at the aluminum/explosive interface. The initial shock velocities are used to determine states on the unreacted explosive Hugoniot, and the distances and times when the shock velocities abruptly increase are taken to be the run distances and times to detonation.

FIGURE 1. Experimental geometry for the wedge test
The experimental geometry for the embedded gauge experiments is shown in Fig. 2. A 12.7 mm thick, 60 mm diameter Lexan flyer plate impacted a target consisting of a 6 mm thick, 90 mm diameter Lexan buffer plate and a 25 mm thick, 50.8 mm diameter LX-19 charge. This charge was held in place by a 3 mm thick Lexan ring. Six 0.3 mm thick Teflon-insulated manganin gauges were placed in pairs along the center line of the charge at distances of 0, 6, and 12 mm. Three experiments were fired in a 100 mm powder gun with Lexan flyer velocities of 0.54 mm/ps, 0.56 mm/ps and 0.851 mm/ps, producing initial shock pressures of approximately 1.1 GPa, 1.3 GPa and 2 GPa, respectively. One experiment was fired using PBXC-19 and a Lexan flyer velocity of 0.867 mdps, producing an initial shock pressure of 2.1 GPa. The measured changes in resistance of the manganin gauge elements were converted to pressure histories and compared to Ignition and Growth calculations.

**REACTIVE FLOW MODELING**

The Ignition and Growth reactive flow model uses two Jones-Wilkins-Lee (JWL) equations of state, one for the unreacted explosive and another one for the reaction products, in the temperature dependent form:

\[
p = A e^{R_1 V} + B e^{R_2 V} + \omega C_v T
\]

where \( p \) is pressure in Megabars, \( V \) is relative volume, \( T \) is temperature, \( \omega \) is the Gruneisen coefficient, \( C_v \) is the average heat capacity, and \( A, B, R_1 \) and \( R_2 \) are constants. The equations of state are fitted to the available shock Hugoniot data. The reaction rate law is:

\[
dF/dt = I(1-F)\left(\rho/\rho_0\right)^{a} + G_1(1-F)\left(F_F^d\right)^c p^4 p^2 G_2(1-F)\left(F_F^d\right)^e p^2 G_1(1-F)
\]

where \( F \) is the fraction reacted, \( t \) is time, \( \rho \) is the current density, \( \rho_0 \) is the initial density, \( p \) is pressure in Megabars, and \( I, G_1, G_2, a, b, c, d, e, g, x, y, \) and \( z \) are constants. As explained in previous papers(4), this three term reaction rate law models the three stages of reaction generally observed during shock initiation of heterogeneous solid explosives. The equation of state parameters for LX-19, aluminum, Lexan, and Teflon, and the Ignition and Growth rate law parameters used in the reactive flow calculations are listed in Table 1. The reaction rates are the same as those used for LX-10 (5), except that the hot spot growth rate parameter \( G_1 \) in Eq. (2) has been increased from 120 to 150.

**COMPARISON OF RESULTS**

Table 2 contains the comparison between the experimentally measured run distances and times to detonation and the Ignition and Growth results for the three LX-19 wedge tests. The transition to detonation was very rapid in both the experiments and calculations, so the exact location of the transition to detonation was easily located. The Ignition and Growth unreacted Hugoniot yielded excellent agreement with the three measured shock velocities preceding the transitions to detonation. The reaction rate law with \( G_1=150 \) yielded excellent run distances and times to detonation for LX-19.

A much more difficult test of a reactive flow model is the calculation of measured pressure histories during a shock initiation experiment. Figure 3 shows the comparison between the manganin gauge records and the calculated pressure histories for the lowest impact velocity experiment on LX-19, 0.54 mm/\( \mu \)s, which produces a shock pressure of 1.1 GPa. The gauges and calculations both show a slow growth of pressure for 6 to 8 \( \mu \)s, followed by a more rapid increase over the next 5 to 7 \( \mu \)s. This pattern is nearly identical to that observed for LX-10 and LX-14, although the time delay is slightly shorter and the growth slightly faster for LX-19. Figure 4 contains records for a higher Lexan flyer velocity, 0.56 mm/\( \mu \)s, which results in a pressure of 1.3 GPa. The measured growth of reaction at the two 0 mm gauges is much more rapid than at the other four gauges and the six gauges in Fig. 3. The calculated pressures show...
TABLE 1. Equation of State and Reaction Rate Parameters

<table>
<thead>
<tr>
<th></th>
<th>Unreacted JWL</th>
<th>Product JWL</th>
<th>Reaction Rate Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_0$</td>
<td>$1.942 \text{ g/cm}^3$</td>
<td></td>
<td>$l=7.43 \times 10^{11}$</td>
</tr>
<tr>
<td>$A$</td>
<td>$4444 \text{ Mbar}$</td>
<td>$16.379 \text{ Mbar}$</td>
<td>$G_2=400$</td>
</tr>
<tr>
<td>$B$</td>
<td>$0.0513014 \text{ Mbar}$</td>
<td>$1.8629 \text{ Mbar}$</td>
<td>$e=0.333$</td>
</tr>
<tr>
<td>$R_1$</td>
<td>$13.5$</td>
<td>$6.50$</td>
<td>$a=0.0$</td>
</tr>
<tr>
<td>$R_2$</td>
<td>$3.35$</td>
<td>$2.70$</td>
<td>$b=0.667$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$0.8695$</td>
<td>$0.55$</td>
<td>$x=20.0$</td>
</tr>
<tr>
<td>$C_V$</td>
<td>$2.7814 \times 10^{-5} \text{ Mbar/K}$</td>
<td>$1.0 \times 10^{-5} \text{ Mbar/K}$</td>
<td>$z=2.0$</td>
</tr>
<tr>
<td>$T_0$</td>
<td>$298^\circ \text{K}$</td>
<td></td>
<td>$G_1=150$</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>$0.0454 \text{ Mbar}$</td>
<td></td>
<td>$FG_{1\text{max}}=0.3$</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>$0.002 \text{ Mbar}$</td>
<td></td>
<td>$FG_{2\text{min}}=0.5$</td>
</tr>
</tbody>
</table>

2. Gruneisen Parameters for Inert Materials

\[
p = \rho_0 c^2 \left[ 1 + (1-\gamma)/2 \mu - a/2 \mu^2 \right] / \left[ 1 - (S_1 - 1)\mu - S_2\mu^2 - (\mu + 1) - S_3\mu^3 - (\mu + 1)^2 \right] + (\gamma_0 + a\mu)E
\]

where $\mu = p/p_0 - 1$ and $E$ is thermal energy

<table>
<thead>
<tr>
<th>Inert</th>
<th>$\rho_0 (\text{g/cm}^3)$</th>
<th>$c (\text{mm/\mu s})$</th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$\gamma_0$</th>
<th>$a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-T6 Al</td>
<td>2.703</td>
<td>5.24</td>
<td>1.4</td>
<td>0.0</td>
<td>0.0</td>
<td>1.97</td>
<td>0.48</td>
</tr>
<tr>
<td>Lexan</td>
<td>1.193</td>
<td>1.933</td>
<td>2.04</td>
<td>0.0</td>
<td>0.0</td>
<td>0.61</td>
<td>0.0</td>
</tr>
<tr>
<td>Teflon</td>
<td>2.15</td>
<td>1.68</td>
<td>1.123</td>
<td>3.98</td>
<td>-5.8</td>
<td>0.59</td>
<td>0.0</td>
</tr>
</tbody>
</table>

TABLE 2. Experimental and calculated wedge test results

<table>
<thead>
<tr>
<th>Flyer Velocity</th>
<th>Pressure</th>
<th>Experimental results</th>
<th>Calculated results</th>
</tr>
</thead>
<tbody>
<tr>
<td>(mm/\mu s)</td>
<td>(GPa)</td>
<td>Distance (mm)</td>
<td>Time (\mu s)</td>
</tr>
<tr>
<td>0.3335</td>
<td>1.437</td>
<td>&gt;29</td>
<td>9.4</td>
</tr>
<tr>
<td>0.05804</td>
<td>2.663</td>
<td>13.17</td>
<td>3.38</td>
</tr>
<tr>
<td>0.08004</td>
<td>3.924</td>
<td>8.89</td>
<td>2.47</td>
</tr>
</tbody>
</table>

FIGURE 3. Pressure histories for LX-19 impacted at 0.54 mm/\mu s by a Lexan flyer plate

FIGURE 4. Pressure histories for LX-19 impacted at 0.56 mm/\mu s by a Lexan flyer plate
fast reaction to 10 GPa at 15 to 18 μs, at which time the 6 mm and 12 mm deep gauges may have been affected by the radical rarefaction wave.

At higher shock pressures, the gauge records and calculated pressure histories agree more closely. Figure 5 shows the pressure histories resulting from a Lexan flyer velocity of 0.851 mm/μs, which shocks the LX-19 to ~2 GPa. The agreement is excellent, even during the rapid pressure increase from 7 to 20 GPa in 2 μs. The LX-19 pressures reach 20 GPa at about 11 μs, whereas the pressures in a similar experiment on LX-14 reached 15 GPa in 12 μs with similar rates of pressure increase. Figure 6 contains the pressure histories for an experiment using PBXC-19 impacted by a Lexan flyer at 0.867 mm/μs, imparting ~2.1 GPa to the explosive. The Ignition and Growth model parameters were not changed, except for the initial density of PBXC-19, which is 1.896 g/cm³. The calculated pressure histories are very close to the experimental records at this shock pressure, which causes rapid reaction and then detonation a few mm beyond the last gauge.

**SUMMARY**

The shock sensitivity of two ε-CL-20 formulations has been quantitatively demonstrated to be slightly greater than that of similar formulations based on HMX. The Ignition and Growth reaction rates for ε-CL-20 formulations are the same as those previously developed for similar HMX-based formulations, except for a 25% increase in the hot spot growth coefficient G₁ from 120 to 150, and accurately calculate the measured pressure histories.

**ACKNOWLEDGEMENTS**

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**REFERENCES**


4. Bui, Q. T., Naval Air Warfare Center, China Lake, formulated and kindly provided the PBXC-19.