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NONIDEAL DETONATION AND INITIATION BEHAVIOR OF A COMPOSITE SOLID ROCKET PROPELLANT

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Shock initiation and detonation behavior of an HMX/AP/Al rocket propellant was studied for nonideal character. Low detonation velocities and unusual shock initiation behavior were observed. Failure to propagate steady detonation in cylinders of the propellant was also noted.

A nonideal explosive has been defined by C. Mader as one having a detonation velocity, C-J pressure, or an expansion isentrope significantly different from those predicted by an equilibrium thermodynamic calculation such as BKW. In this paper we are concerned with deviations from predicted values of detonation velocities, atypical shock initiation behavior, and detonation failure in cylinders of explosive.

Two types of experiments were done on SPIS-44, an Air Force propellant. Plane shock initiation wedge experiments were performed to study the nature of the buildup to detonation. One also obtains a measure of detonation velocity and particle velocity associated with the front. Bare cylinders of the propellant were fired as rate sticks to determine failure diameter and detonation velocity.

The wedge experiments show unusual initiation behavior, a low detonation velocity, and a free-surface particle velocity indicative of some degree of reaction. The rate sticks showed that the failure diameter is greater than 50 mm. In fact, a 74-mm-diameter rate stick may have been heading for failure after propagating six diameters with decelerating velocity. The nature of the shorting pin signals also indicates unusual behavior.

The formulation for SPIS-44 is given in Table I. It is 20/49/21 wt% HMX/AP/Al, and has an inert binder. Its density, 1.83 g/cm^3, is full density.

Figure 1 shows the nature of the unusual character of the buildup to detonation in SPIS-44. For comparison, typical buildup curves for two other formulations are shown. Formulation A with 44/16/19 wt% HMX/AP/Al plus binder, has trajectories typical of heterogeneous explosives and its detonation velocity of 7.8 $\pm$ 0.3 mm/µs and product velocity against ambient air of 8.2 $\pm$ 0.7 mm/µs agree with a BKW calculation (cf. Ref. 1 for more details). The trajectory for Formulation B (29/36/18 wt% HMX/AP/Al plus binder) looks like that of formulation A, but both detonation velocity 6.6 $\pm$ 0.1 mm/µs and product velocity of 6.0 $\pm$ 0.2 mm/µs are well below BKW values of 8.0 and 8.6 mm/µs, respectively. So Formulation B is in some sense nonideal. The measured detonation velocity is evidence of incomplete reaction before the sonic surface driving the detonation front. A BKW calculation treating the AP as inert gives a detonation velocity of 6.5 mm/µs in agreement with the measured value. Calculated product velocity is 5.8 mm/µs, also in agreement with measured values.

Table 1

SPIS-44 Propellant Formulation

Ingredient	Average Particle Size (µm)	Weight Percent
Ammonium Perchlorate	200	28
" "	6	21
Cyclotetramethylene Tetranitramine	9	20
Aluminum	6	21
Hydroxy-terminated Polybutadiene	-	7.27
Polybutene Oil	-	2.00
Isophorene Diisocyanate	-	0.51
Bonding Agent from Glycidol, Tetraethylene Pentamine and Acrylonitrile	-	0.15
Methylene Bis(Tertiarybutyl Phenol)	-	0.07

The SPIS-44 trajectories show behavior different from that of the other formulations. There is some acceleration for 7.0 GPa input stress, and there is some evidence of a transition for the 11.7 GPa shot. But the accelerations involved are much lower than for other, more sensitive formulations. Most explosive formulations have trajectories which can be modeled by an acceleration which diverges as the transition is approached. For formulation C the acceleration through the transition region for the 11.7 GPa shot was nearly constant at 0.8 $mm/\mu s^2$, whereas the peak acceleration for formulation B was 4.8 $mm/\mu s^2$ and 6.8 $mm/\mu s^2$ for formulation A (Fig. 2). For even higher input stresses the SPIS trajectories show no transitions, but the detonation velocities are increased. The detonation velocities (Fig. 1) correspond to incomplete reaction. BKW calculations predict 8.0 mm/μs. For the 25.7 GPa shot, the flow velocity at the wedge heel was 6.9 mm/μs against ambient air. This compares with 8.6 mm/μs expected for complete reaction and 4.2 mm/μs for twice the particle velocity of the Hugoniot state at the input face of the wedge. So the 6.9 mm/μs flow velocity is consistent with incomplete reaction near the detonation front.

The detonation velocity increases with increased input stress, an indication of overdriven detonation. The problem is to explain the nature of the transition for the 11.7 GPa shot. It could be interpreted as the buildup phase of an overdriven detonation. BKW results for 0% AP reacted give a detonation velocity of 5.8 mm/μs and a CJ pressure of 12.2 GPa; for 15% AP reacted the detonation velocity is 6.2 mm/μs with CJ pressure of 15.0 GPa.

The question then remains whether unsupported detonation is possible in this material. In an attempt to answer this question, several rate stick/plate-dent shots were fired. Cylinder diameters were 25, 51, and 74 mm. The mild-steel witness plates were 51 mm thick.

The first shot was a simple plate-dent experiment with a 25.2-mm-diam charge, 101.2 mm long. The stick was initiated by a 40-mm-diam planewave lens and 6.4 mm of PBX-9404 (strongly overboosted). There was no deformation of the steel plate (Fig. 1). A good deal of black smoke emanated from the shot, and a few 1-cm chunks of unconsumed propellant were found lying beside the steel plate.

The next shot was a 73.5-mm-diam rate stick 407.7 mm long. The shot was placed in a

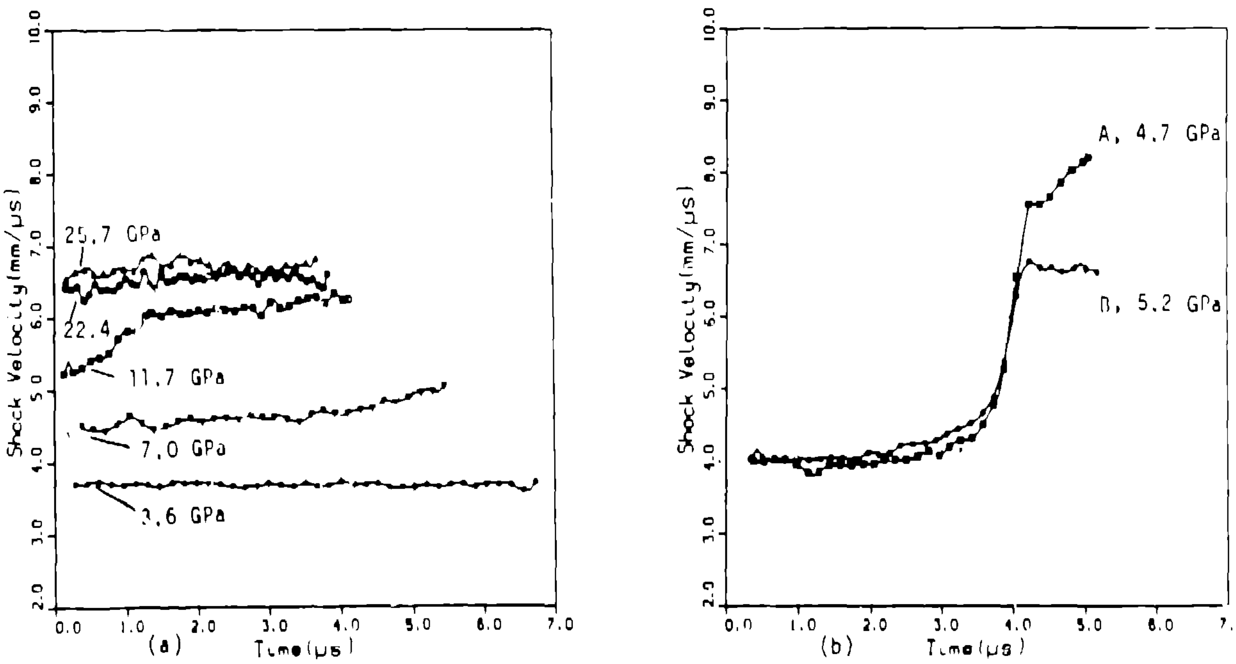

Fig. 1. Shock velocity-time trajectories obtained by differentiating the shock position-time trajectories measured in wedge experiments. The shock velocity was obtained as the slope calculated by a running linear least-squares fit to the data. Only every other point is shown. (a) shows the trajectories for SPIS-44 for a number of input pressures. (b) shows results for two other propellants, one ideal and one nonideal. The pressures given are the input pressures.

Styrofoam box for temperature control at 19 ± 1°C. The stick was initiated by a 100-mm-diam planewave lens and 10.4 mm of PBX-9404. There were nine SPIS-44 segments with 51-µm-diam, insulated, magnet-wire pins between segments. Two wires were laid parallel along a diameter a few millimeters apart. A sizeable dent was made in the steel plate (Fig. 1), but the pin signals were erratic (65 V on the pins). Only four of 10 pin signals looked normal. The segmental velocities from the normal signals are displayed in Fig. 3.

The final shot was a 50.8-mm-diam stick 235.6 mm long. The shot was placed in a Styrofoam box for temperature control. Shot temperature was 20.5°C. The stick was initiated by a 56-mm-diam planewave lens and 12.7 mm of PBX-9404. In order to try to solve the pin problems, two new pin designs were tried. The first set used one insulated wire and one bare ground wire making an "x" across the center of the segment face, with about a 15° angle between the wires. This set did not require ionization of the explosive for shorting, but was shorted by mechanical action of the shock wave. The second set used a pair of bare wires lying parallel a few millimeters apart and extending about a centimenter in from the edge of the face (50 V on the pins).

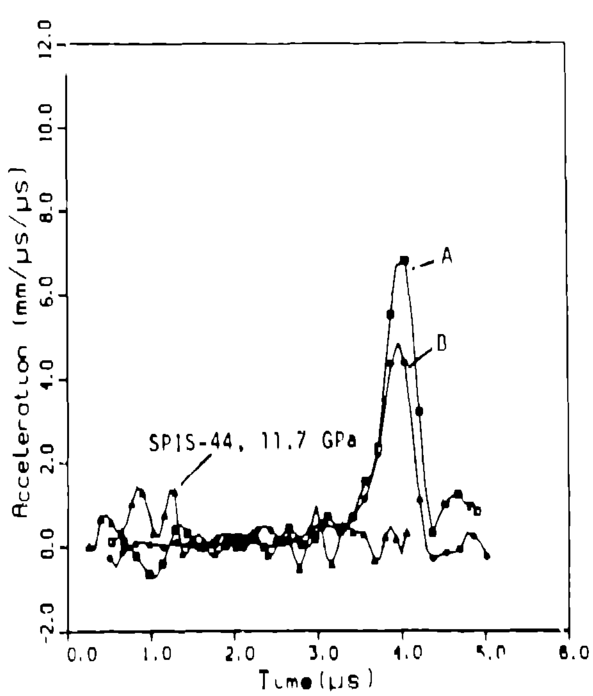

Fig. 2. Acceleration-time trajectories obtained for three propellant formulations by numerical differentiation of trajectories in Fig. 1. Peak acceleration decreases with increasing departure from ideality.

The first set gave good, normal signals. Those from the second set were not sharp, normal signals except for the first two. This indicates that the incompletely reacting SPIS-44 propellant does not provide a good electrical path for shorting pins. The segmental velocities obtained from the first set of pins are shown in Fig. 3. Note that shorting signals were not received from the ends of the last two segments. This is consistent with the fact that the steel witness plate was not deformed. There was some black residue on it.

In conclusion, SPIS-44 propellant failed at 25 and 51 mm diam. For the 51-mm-diam shot strongly initiated by PBX-9404, it propagated about four diameters before failing. From a study of Fig. 3, noting that the shock in the last segment of the 74-mm-diam stick was propagating at 5.35 mm/µs, it appears that the reactive wave in the stick may have been headed for failure after propagating something more than six diameters. This is consistent with the suggestion of D. Price (2) that Group 2 explosives fail slowly. These results do not entirely lay to rest the question of whether unsupported detonation is possible in SPIS-44 propellant. The data do indicate that failure occurs in sticks less than 50 mm diam and perhaps up to 74 mm diam. They add weight to the earlier suggestion that the trajectories observed in shock-initiation wedge tests on SPIS-44 are evidence for overdriven, nonideal flows.

There are several reasons why the reactive flow might be nonideal in these materials.

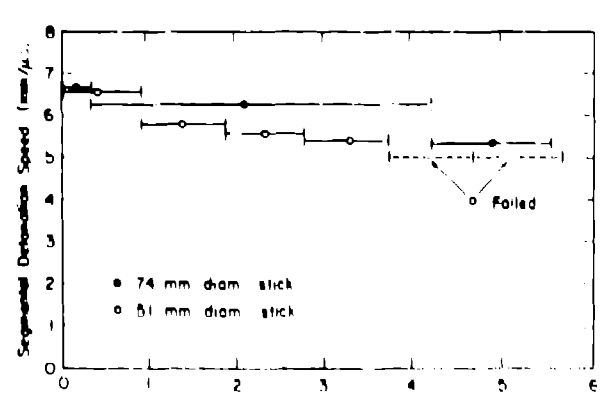

Fig. 3. Detonation velocity measured by transit time through cylindrical segments vs the ratio of propagation distance to cylinder diameter. Detonation in the 51-mm-diameter stick failed after propagating almost 4 diameters. Detonation in the 74-mm-diameter stick may be on its way to failure after propagating 5 1/2 diameters.

These propellants are composite materials with fuel and oxidizer on separate particles, except for the HMX. This means that the reaction rate (progress towards complete decomposition) can be diffusion-limited. Furthermore, the pressure in the reaction zone may remain low because of a low number of moles of gas per cubic centimeter in the reaction products. The propellant is also oxygen-deficient.

ACKNOWLEDGMENTS

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