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ANALYSIS OF SHOCK WAVE AND INITIATION DATA FOR SOLID EXPLOSIVES

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ABSTRACT

If the usual analysis of shock-wave data is made for polycrystalline plastic-bonded HMX and pressed TNT the experimental data extrapolate to the detonation pressure point rather than to the peak spike pressure point. This is indicative of a reactive wave, which is to be expected. Limitations based on the assumptions and analysis are discussed to show that it is not possible to infer any information about the shock properties of unreacted explosive from the available shock-wave data for solid explosives.

Since no calculational model is available which will permit the computation of the details of initiation of solid explosives, empirical relationships are presented to summarize the data for engineering purposes.

INTRODUCTION

The initiation of solid explosives by shock waves has been discussed by Campbell and co-workers.¹ They have shown that shock initiation takes place in the following way. The shock wave in the polycrystalline explosive is always rough because of the small local discontinuities distributed throughout the material. Therefore, there will be small local convergences of the shock wave and the associated mass flow, with local high temperature regions. Reaction takes place in these small regions of convergence, and the energy released makes a major contribution to initiation. The reactive wave proceeds at a slowly increasing velocity for a distance which is a function of the initial shock pressure. Then the velocity increases in a short but observable distance to the value associated with the high-order detonation. The velocity transition is not abrupt, as is the case for liquids, nor is there any strong overshoot in the detonation velocity, again in contrast to liquids. This series of events is illustrated in Fig. 1.

Gittings² has shown that explosive may be initiated by impacting it with very thin foils. These foils produce a very short pressure pulse in the explosive, showing that energy which is released by the shock interactions is released very near to the shock front. This rapid release of energy will affect the shock front soon after the shock wave enters the explosive. Mader^{3, 4} has shown by calculational experiments how small hot spots are formed and that their energy is released a very short time after the wave has passed.

All evidence indicates that shock-waves in polycrystalline explosive are reactive waves; thus measurements of shock waves should not be thought to give information about the shock properties of unreacted explosive. In addition, the shock wave in a polycrystalline explosive is not smooth and plane, and energy added to the wave from reaction at small hot spots is not

added uniformly over the wave surface.

The Hugoniot curves of solid polycrystalline explosives have been reported by several authors.^{1,5,6} In two of these studies the curves have been extended to estimate the spike pressure in the unreacted explosive. In this paper we present data obtained for plastic bonded HMX (PBX-9404) and pressed TNT, and show that, if the usual assumptions and treatment are made of the data, the Hugoniot curves extrapolate to the detonation pressure (C-J pressure)* rather than to the spike* pressure. Because of the complex nature of the mechanism of shock propagation in polycrystalline materials and, in particular, in a polycrystalline explosive which is known to be reacting, it is not possible to determine whether the assumptions and treatment of the data are correct. Rather, the data are treated in an empirical manner which permits the summarization of the experimental data compactly and in a manner suitable for engineering purposes.

* Because of the questions concerning the use of the term C-J pressure^{7,8} we will use the term detonation pressure to refer to the abrupt change in pressure observed in reaction zone studies. This is the same point that has previously been called the C-J pressure. The term spike pressure means the pressure at the leading edge of the detonation wave.

SHOCK MEASUREMENTS

Shock waves in solid explosives have been studied by the wedge technique in which a plane, uniform shock wave is sent into a wedge-shaped piece of explosive and the position of the intersection of the shock wave and the inclined face of the explosive recorded as a function of time with the smear camera. Solid explosives have also been studied by the pellet technique in which the transit time of a shock wave through a thin pellet of explosive is measured either with a smear camera or with pins located at the back and front surfaces. The wedge technique gives a complete time history of the shock wave as it propagates in the explosive, while the simpler pellet technique provides only an average shock velocity. This difference is illustrated in Fig. 1 as the difference between U_s and $\bar{U}_s$.

The analysis of the data obtained from such studies is normally performed by assuming that the flow is one-dimensional and laminar and that the pressure at the interface where the shock enters the explosive is changing only slowly with time. These assumptions are not correct, but no practical alternative has been proposed. It is not possible to estimate the magnitude or sign of the errors which may be introduced by these assumptions.

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Table 1

Sound Velocities for Pressed TNT and PBX-9404

	Pressed TNT	PBX-9404
Density g/cc	1.635 ± 0.005	1.83 ± 0.01
Sound Velocities		
Longitudinal, mm/μsec	2.586 ± 0.080	3.060 ± 0.056
Shear, mm/μsec	1.330 ± 0.050	1.612 ± 0.056
Bulk, mm/μsec	2.08 ± 0.13	2.43 ± 0.07

Data from wedge-type experiments for PBX-9404 are shown in Fig. 2 and in Fig. 3 for pressed TNT. The TNT data have been supplemented by pellet-type measurements made by Garn.⁹ These measurements by Garn on pressed TNT were made in 1958 and have not been reported previously. In addition, data on liquid TNT obtained by Garn¹⁰ are shown in Fig. 3. The linear fit of the data for pressed TNT agrees within the expected experimental error with values reported by Liddiard⁵ for cast TNT.

Vasil'ev and co-workers¹¹ have reported measurements of the isothermal compressibility of TNT up to 21 kbar. These measurements have been transformed to the plane of the figure by assuming that the isotherm and the Hugoniot curve are congruent up to 21 kbar.

McQueen and Marsh¹² have shown that for a large number of solid inorganic materials the shock velocity and particle velocity are linearly related in regions where no shock-induced phase transitions occur. They also showed that the intercept for zero particle velocity is the bulk sound velocity. The bulk velocity is defined by equation (1)

$$C_0 = (k/\rho_0)^{1/2} \quad (1)$$

where k is the isentropic modulus of volume elasticity and ρ_0 is the density. The bulk sound speed is not measured directly for solid materials but is obtained from measurements of the longitudinal and shear sound velocities through equation (2).

$$C_0^2 = C_L^2 - (4/3) C_s^2 \quad (2)$$

C_L is the longitudinal sound velocity for a wave front in a specimen whose diameter is large compared to the wave length. C_s is the shear sound velocity defined in the usual manner. Table 1 gives the sound speed measured by

Edwards, Finley and Grimm¹³ at Los Alamos. For both TNT and PBX-9404, preliminary analysis of the experimental shock-wave data showed no significant difference existed between the intercept value and the bulk sound velocity. The lines labeled "experimental" in Figs. 2 and 3 were obtained from least-squares fit which included the measured bulk sound velocity with a weight of 4 to adjust for the difference in the expected standard deviations.

detonation has a shock wave propagating in the unreacted explosive, heating the explosive, and causing reaction to take place after an induction period. The pressure and particle velocity are highest in the unreacted explosive and fall as the reaction proceeds. When the reaction is complete the rate of fall of pressure becomes small. Estimates of the particle velocity corresponding to the spike pressure and the detonation pressure have been obtained by Craig^{8, 14} for PBX-9404 and pressed TNT and by Dremine¹⁵ for pressed TNT. These points are plotted in the respective figures together with the highest measured points on the reaction zone. These data had to be analyzed on the basis that the explosive is a continuum and that the polycrystalline nature did not affect the measurement. Again this is a questionable assumption, but no other basis is available.

It is interesting to try to interpret the curves shown in Figs. 2 and 3 with the usual treatment given shock-wave data. In the shock velocity vs particle velocity plane, the shock loci for most materials are very nearly linear, provided no shock-induced phase changes occur. It is therefore to be expected that a straight line from the bulk sound velocity to the estimated spike pressure point would approximate the shock locus of the unreacted explosive. This line has been drawn in Figs. 2 and 3 and is labeled "Unreacted" in Fig. 2 and shown as a dashed line in Fig. 3. In both cases the experimental shock points appear to lie along a line which can easily be drawn through the detonation pressure point, indicating that the experimentally measured curves represent partially reacted explosive. This behavior of the curves for solid explosives can be contrasted with that for liquid explosives. Studies of shock initiation of liquid explosives show that the shock-wave data for liquids are for the unreacted material. For liquid TNT the detonation pressure point reported by Davis, Craig, and Ramsay⁷ has a particle velocity of 1.85 mm/μsec and a detonation velocity of 6.59 mm/μsec. If this point were plotted in Fig. 3, it would lie on the linear extension of the experimentally measured curve for the solid. A linear fit of the shock-wave data for the liquid cannot include this point. This conclusion, that the experimentally measured Hugoniot curves for liquids do not extrapolate in a linear manner to the detonation point, is confirmed by data for nitromethane.^{6, 7}

The usual model of one-dimensional, laminar

It would at first appear that the isothermal compressibility data for pressed TNT indicate that the experimentally measured Hugoniot curve represents unreacted explosive. However, when a similar comparison is attempted between isothermal curves and the measured Hugoniot loci for other materials (mostly metals and inorganic compounds), the slope of the isothermal curve in the plane of shock velocity vs particle velocity is generally a factor of two higher than the slope of the Hugoniot curve. If anything, one would expect the isothermal curve to be less steep than the Hugoniot curve. Therefore, the use of the isothermal curve to determine the Hugoniot curve for the unreacted explosive must be suspect and the question remains open as to whether the true Hugoniot curve for pressed TNT can be approximated with a straight line in the shock velocity vs particle velocity plane.

It is our opinion that the measured Hugoniot curve should not be used to infer properties of the unreacted explosive until the propagation of shock waves in polycrystalline materials and the initiation of solid explosives is more completely understood. We also believe that the very complex initiation behavior of polycrystalline explosives cannot be calculated from these data at the present time.

EMPIRICAL APPROACH TO SHOCK INITIATION

The complexity of the mechanism of shock initiation of polycrystalline explosives makes it impossible for us to calculate in detail the events leading up to the transition from a shock wave to a detonation wave. Therefore, we are forced to be less ambitious and to look for empirical relationships which make it possible to summarize experimental data compactly and to use them for engineering purposes.

While the pressure calculated from the wedge and pellet experiments is not a true measure of the conditions at the boundary, we have found it quite useful and convenient for correlating such factors as distance of run and time of run to detonation for various booster systems. It has been found that a plot of the log of the distance of run of the shock wave vs the log of the pressure of the initiating shock wave as it enters the explosive is linear over an appreciable range. This relationship is shown for several explosives in Fig. 4. The data available for PBX-9404, which cover the widest pressure range, indicate that estimates made from curves of this type will be accurate to about 25%. The low pressure points for PBX-9404 correspond to velocities only 0.1 to 0.2 mm/ μ sec faster than the longitudinal sound velocity.

Usually the easiest measurement to make on small explosive systems is a measurement of transit time. If the explosive has been under-initiated it will take longer for the wave to traverse the piece than if the wave traveled at steady-state velocity throughout. The difference between the measured transit time and the time calculated on the basis of steady-state velocity is called the excess transit time. Because of the complex relationships between shock velocity,

pressure, and distance of run, it is usually not possible to relate the excess transit time to distance of run and pressure. If data from wedge-type experiments are available for a particular explosive it is possible to construct curves of the type shown in Figs. 5 and 6. The excess transit times shown were calculated from wedge-type experiments by dividing the measured distance of run by the detonation velocity and subtracting this calculated time from the measured time to detonation. In this calculation the very small excess time, which exists because the detonation does not reach steady-state velocity at the position measured as the point of onset of detonation, is neglected. This error is labeled as " t_e " in Fig. 1, and its size has been exaggerated for the purpose of illustration. In general, the increase in velocity is less than 200 m/sec. These curves have proved useful when it has been necessary to make a semi-quantitative analysis of small charges.

As the initiation of solid explosives depends on such factors as particle size, density and exact composition, it seems that general curves for an explosive cannot be given, but that they must be produced for the particular lot being used.

SUMMARY

It has been shown for PBX-9404 and pressed TNT that, if the common treatment is made of the shock-wave data, the curves can be drawn through the detonation pressure point rather than the peak spike pressure point. If the usual assumptions are correct, then either the curves must be for partially reacted explosive or the curves must show a drastic change in slope above the experimentally measured range. Some of the inadequacies of the assumptions and analysis have been pointed out. It has been suggested that there is no model available now by which one can calculate the details of the shock initiation of polycrystalline explosives.

A empirical linear relationship between the log of the shock pressure and the log of the distance of run to initiation has been presented in the hope that it may prove useful for engineering purposes. It has also been shown that the shock-wave data taken from wedge experiments may be used to relate the easily measured excess transit time to the initiating pressure and to the distance of run to detonation. These relationships have often been useful in obtaining a semi-quantitative analysis of the behavior of a system.

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Fig. 1. Space-Time Plot of Shock Initiation in a Solid Explosive.

- D = Steady-state detonation velocity
- X = Measured distance to detonation
- t = Measured time to detonation

- * = Excess transit time
- t_c = Calculated excess transit time
- t_e = Error in calculated excess transit time
- $\bar{U}_s$ = Average initiating wave velocity
- U_s = Initial shock velocity as measured

Fig. 2. Hugoniot Curves for Plastic-Bonded HMX. The vertical lines represent the error of the measured shock velocities. The experimental line is a least-squares fit of the data including the bulk sound velocity. The line connecting the spike pressure and the bulk sound velocity is an estimate of the Hugoniot curve for the unreacted explosive.

Fig. 3. Hugoniot Curves for TNT. The dashed section of the experimentally measured curve represents an extrapolation based on the assumption that the curve is linear. The dashed line connecting the bulk sound velocity with

the spike pressure is an estimate of the Hugoniot curve for the unreacted explosive.

Fig. 4. Relationship Between Distance to Detonation and Initial Shock Pressure for Various Explosives. The open symbols for PETN represent the maximum and minimum distances which could be measured. The points are located at the calculated pressures. The data for PETN are taken from Seay and Seely¹⁶.

Fig. 5. Distance of Run to Detonation vs Excess Transit Time for Plastic-Bonded HMX. $\rho_0 = 1.83 \pm 0.01$ g/cc.

Fig. 6. The Relationship Between the Initial Pressure and the Excess Transit Time for Plastic-Bonded HMX. $\rho_0 = 1.83 \pm 0.01$ g/cc.