On the Coupling of Detonation Drive to Metals

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ABSTRACT

A comparison between results of CTH wave-code calculations and Gurney-model calculations has been carried out for an open-face sandwich explosive assembly. The results reveal three regimes of detonation drive dominated by (a) momentum transfer, (b) energy transfer and (c) gas dynamics. Higher efficiency in explosive drive of metal was recognized in the regime dominated by gas dynamics. Interposing a low-impedance buffer material between detonating explosive and driven steel was found to increase momentum transfer markedly at high values of \( M/C \). This effect diminished as \( M/C \) was reduced, and disappeared when \( M/C < 1 \). A similar but less pronounced effect was noted when the intervening material between the detonating explosive and the steel was a thin laminate of high- and low-impedance materials.

INTRODUCTION

In many applications in which detonation of explosives is used to accelerate metals, the explosive is in direct contact with the metal at the time of detonation. We have called this direct drive of the metal. In some cases, other materials intervene between the explosive and the metal, and this affects the coupling of detonation output to the metal. Presence of such intervening material or of a gap between the explosive and the metal may result in what we have called indirect drive of the metal (Ref. 1).

In this paper we report on one-dimensional calculations done with and without intervening materials, and compare results obtained with the CTH wave-propagation code with those obtained by use of the simple Gurney model. All calculations were done with open-sandwich geometry (Fig. 1), i.e., a slab of explosive with a free face on one side and contact with the metal or intervening material on the other. Metal velocity was evaluated after a seven-fold expansion of the detonation product gases, a criterion for completion of energy transfer suggested by Kury et al. (Ref. 2). Gurney-model estimates of terminal velocity of the metal were made by use of the Gurney equation for open-face sandwich geometry (see Ref. 3).

DESCRIPTION OF MODELS AND CONFIGURATION

The geometry and materials of problems addressed are shown in Fig. 1. The behavior of interest was the velocity imparted to a steel plate by detonation of PBX-9501 explosive. In some cases that were analyzed, a layer of silicone rubber (Sylgard 184) intervened between the explosive and the steel. Dimensions as well as presence of the silicone were varied over a wide range to allow us to analytically investigate regimes of behavior in the detonation drive of inert materials. All materials were assumed to be infinitely wide plates, so the flow
Driven Velocity

Initiate Detonation Here

Fig. 1 Open-face sandwich configuration.

was always one-dimensional and there was no influence of side effects. No experiments were done; this study was strictly analytical. In code calculations, detonation was initiated on the free surface of the explosive.

Both of the models that were compared, the CTH code and the Gurney model, analyzed one-dimensional rectilinear flows. CTH results are assumed to be more accurate because they account for shock-wave flows and reflections due to mechanical-impedance mismatches. But the Gurney model is of interest because of:

1. the analytical nature of the closed-form equations that it produces,
2. opportunities for analytical combination with other physics to optimize a solution or parameterize a problem, and
3. insight that it can provide, described here, about regimes in the detonation drive of metals.

The CTH wave-propagation code (Ref. 4) is capable of analyzing shock-wave flows in one, two or three dimensions. Constitutive relations used to describe the materials in this problem were of the simplest types, involving principally the shock Hugoniots and isentropes (which govern sound speed behind the shock front). Detonation of PBX-9501 explosive was treated by specification of the detonation velocity and initial density, and the detonation product isentrope was described within CTH by use of a JWL equation of state. Strength and elastic limits of inert solid materials were not of concern in this problem.

The Gurney equation for an open-face sandwich configuration, such as shown in Fig. 1, is

\[
v = \sqrt{2E} \left[ \frac{1 + \frac{2M}{C}}{6 \left( 1 + \frac{M}{C} \right)} \right]^{1/2} + \frac{M}{C}
\]

where \(v\) is the velocity of the driven inert material, \(\sqrt{2E}\) is the characteristic Gurney velocity for a given explosive, \(M\) is the mass of the driven material, and \(C\) is the mass of the explosive material. This equation was derived using energy conservation and momentum conservation relations, based upon two assumptions due to Gurney (Ref. 5):

1. Every explosive has a certain characteristic specific energy \(E\) (cal/g) that is converted to kinetic energy of the driven metal and the product gases after detonation.
2. Partitioning of the energy and associated momentum between the driven materials and the product gases is calculated by assumption of a uniform product gas density and a linear gas velocity profile. The velocity of driven materials is taken to be uniform throughout their thickness(es).
Analytical Gurney equations for the open-face sandwich geometry and for all other simple geometries contain two dimensionless terms, \( v/\sqrt{2E} \) and M/C, and \( v/\sqrt{2E} \) is an explicit function of M/C. We have chosen to compare CTH wave code results with Gurney model results by plotting \( v \) as a function of M/C, using a value of 2.86 km/s for \( \sqrt{2E} \) for the PBX-9501 explosive (Ref. 6). In these comparisons, the velocity of the steel plate was the parameter of interest. In Gurney calculations, the velocity of any intervening silicone, that was present was taken to be the same as that of the steel because the masses of all materials were summed to evaluate M. In CTH calculations, the velocities of the three driven materials may differ and interfaces may separate if the mechanics works out that way. We were only interested in the velocity of the steel and did not pay attention to whether the intervening materials moved along with the steel or separated from it.

We examined the behavior of \( v \) versus M/C over a wide range of M/C values (several decades in both M/C and \( v \)). We included examples in which the intervening silicone was absent and when the silicone was present. The silicone was always thin in comparison with the steel plate thickness (as suggested by the proportions in Fig. 1), but the explosive layer thickness was sometimes comparable to or smaller than those of the intervening materials.

Gurney equation (1) provides insight into a trend we can expect to see over one region of M/C space. Taking the limit of Eq. (1) for large values of M/C, we find that the equation simplifies to an impulse or momentum expression.

\[
v \equiv \sqrt{2E} \cdot \frac{3}{4} \frac{C}{M}
\]  

Eq. (2) indicates that the steel plate velocity will be proportional to explosive thickness for large values of M/C (M/C >> 1). This solution arises because the kinetic energy contained in the detonation product gases is negligible in comparison with that of the driven steel plate. Due to this linear relationship, detonation of thin layers of explosive on the surface of a large body has been used to test for the response of the large body under impulsive loading (Refs. 3, 7). Impulse equations also describe the way in which rocket engines work. Specific impulse of propellants is an appropriate measure of output because only a small amount of propellant combustion product gas is in acoustic (mechanical) contact with the more massive vehicle at any given time as the product gases flow away from the vehicle.

RESULTS OF CALCULATIONS

Behavior Regimes in Detonation Drive

Velocity as a function of M/C is shown in Fig. 2 for the Gurney model (continuous curve) and for discrete CTH calculations (points). At high values of M/C, the proportional relationship predicted in Eq. (2) is evident. The dashed line on the right side of the plot is drawn in at a log-log slope of -1.0, indicating direct proportionality, and it is placed on the figure to illustrate that the behavior observed among calculated results in the momentum-dominated regime is in line with Eq. (2). The driven-material velocity range in this region is below 350 m/s, and the M/C range is above 7.
Fig. 2 Regimes in detonation drive of inert materials.

At lower values of M/C, energy conservation aspects of the analysis are important. The linear relationship between v and M/C no longer holds because there is a significant amount of kinetic energy in the product gases in this regime. Good agreement is seen between the Gurney model and CTH computations in the velocity range 350 m/s < v < 2900 m/s (where v/√(2E) = 1). The abscissa range is 0.3 < M/C < 7. This is the region where the values of √(2E) are determined from cylinder test data on various explosives (Ref. 7).

The regime in which gas-dynamic expansion dominates is perhaps the most interesting for purposes of this discussion. At lower values of M/C, a deviation arises between CTH results and Gurney results and the deviation becomes progressively greater as M/C is decreased. The Gurney model consistently underestimates the driven velocity. This arises because, as M/C is decreased, the metal is accelerated so quickly that the drive is able to take advantage of an increasingly larger portion of the potential energy of the product gases.

In the more common energy-transfer-dominated regime, approximately 30% of the chemical energy of the explosive is lost during expansion of the gas while it is acoustically out of communication with the metal before acceleration of the metal is completed. Thus the accepted value of Gurney energy E is about 70% of the heat of detonation of the explosive (Ref. 7), and this efficiency of chemical energy conversion to kinetic energy holds over a surprisingly large range of M/C. Using the Fickett-Jacobs cycle
Table I. Direct drive in the gas dynamics regime.

*PBX-9501 detonated at its free surface, in direct contact with silicone.*

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>PBX-9501</th>
<th>Silicone</th>
<th>M/C</th>
<th>(v_{\text{CTH}}, \text{m/s})</th>
<th>(\sqrt{2E_{\text{effective}}}, \text{m/s})</th>
<th>(\text{E}/\Delta H_d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2</td>
<td>0.3226</td>
<td>3110</td>
<td>3125</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>0.1613</td>
<td>4282</td>
<td>3417</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>0.1075</td>
<td>4948</td>
<td>3595</td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>2</td>
<td>0.0538</td>
<td>5922</td>
<td>3869</td>
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<td></td>
</tr>
<tr>
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<td>2</td>
<td>0.0269</td>
<td>6719</td>
<td>4137</td>
<td>1.42</td>
<td></td>
</tr>
</tbody>
</table>

Note: Reference value of \(\sqrt{2E}\) for PBX-9501 in these calculations was 2900 m/s.

(Ref. 8), one may estimate that this 70% efficiency figure corresponds to losing energy remaining in the isentropic expansion of detonation products below 0.1 GPa pressure. So another way of explaining this behavior is to say that, at lower values of M/C, we are able to take effective advantage of energy remaining at a lower-pressure region of the isentrope than we usually do.

In Table I, we calculate the effective values of Gurney velocity \(\sqrt{2E}\) and corresponding values of efficiency expressed as \(\text{E}/\Delta H_d\) for values of M/C < 0.3, based upon our CTH results for direct drive of steel with no intervening material. In this case, the effective value of the Gurney velocity is defined as the value that must assume in order to calculate, with the Gurney open-face sandwich equation, the same result as we obtained with the CTH code. We note that the effective value of the Gurney energy becomes so high that \(\text{E}/\Delta H_d\) exceeds unity. This is not physically plausible, and it indicates that the Gurney model is entirely inappropriate at such low values of M/C.

Effect of Intervening Material

A second point of interest is the effect of intervening material between the explosive and the steel on the velocity driven into the steel. In a study published in this Seminar in 1996 (Ref. 1), it was found that interposing a rubber sheet between a thin layer of sheet explosive and a steel plate affected the coupling of the explosive to the steel. The experimentally observed velocity of the steel was below the value that would be expected on the basis of Gurney calculations. In this study, we looked for the changes in the coupling of the explosive output through intervening material into the steel over a wide range of loading conditions (i.e., M/C values).

First we shall consider the effect of a silicone layer between the explosive and the steel. Fig. 3 is in the same format as Fig. 2, but the different values of silicone thickness are identified by means of different plotting symbols. One can see that, according to CTH calculations, the coupling of explosive energy into the steel is actually increased at high values of M/C when silicone is present. The difference due to the presence of silicone layer was greatest at high values of M/C (a factor of 2 in velocity when M/C was about 260) and virtually disappeared when M/C was about 2. This increase in velocity was found in the calculations in spite of the fact that the silicone added some inert...
Fig. 3 Effects of silicone buffer layer between detonating explosive and driven steel.

mass to the total mass being driven by a given thickness of explosive. Clearly, this indicates that a major change in the mechanics of coupling of explosive output into the steel occurs under high M/C conditions when silicone intervenes between the explosive and the steel. Pressure histories at various points within the steel plate were recorded as part of the output from CTH calculations. Pressure histories in the midst of a 6-mm-thick steel plate driven by 0.4 mm of PBX-9501 are shown in Fig. 4 from calculations both without (a) and with (b) 1 mm of intervening silicone material. Comparison of these two conditions shows that the pressure history is slightly reduced in amplitude but greatly extended in time when silicone is present. From estimates of the PΔt integrals, it is clear that the impulse imparted to the steel is about 50% greater when the silicone is present, and the CTH velocity values corroborate those estimates.

This behavior is a consequence of shock interactions between the detonation products at impact of the detonation wave upon the driven material, and the pressure histories in Fig. 4 indicate reasons for the calculated velocity differences. When a detonation shock encounters a stiff material such as steel (Fig. 4(a)), the product gas flow in the direction of plate motion will be nearly stagnated and stopped, and the strong reflected shock into the detonation products will hasten the product gas flow backward away from the steel. This interpretation is supported by the fact that the positive pressure duration is about 0.3 μs shorter for direct drive into the steel than in the case where silicone was present. The
Fig. 4 Pressure histories at tracer position with steel plate. 0.4 mm PBX-9501 driving 6 mm of steel; 1 mm of silicone between the two in (b) only.

peak pressure driven directly into the steel at the tracer location is higher than that driven indirectly through the silicone. But when the detonation shock encounters silicone, the product gases continue to move forward toward the steel much more rapidly than occurs with direct drive. This extends and increases the pressure level of the flow that follows the initial shock pulse, and that increase in pressure in the later part of the history more than compensates for the lower initial shock pressure. The consequence is that the steel is driven to a higher velocity when silicone was present than when it was not.

This is consistent with our findings of Ref. 1, which considered a rather different set of comparisons. For a given amount of explosive in Ref. 1, it was found experimentally and through CTH calculations that the highest impulse was delivered to a steel plate through an intervening rubber pad by use of the thinnest layer of explosive spread over a larger area. We believe that the reason for lower drive efficiency in the experiments and CTH calculations of Ref. 1, as compared to the CTH calculations reported here, is that the Ref. 1 study dealt with grazing detonation while the current calculations were done with normal detonation incidence.

A likely contribution to the momentum of the steel plate in this study is elastic rebound of the silicone away from the steel, adding momentum to the steel. This type of behavior was experimentally observed in the work reported in Ref. 1. Such rebound could not occur during the first major compressive pressure pulse seen in Fig. 4(b), so the magnitude of momentum contributed by this mechanism could not be large.

CONCLUSIONS

Comparison of CTH wave-propagation code calculations with Gurney model calculations for an open-sandwich configuration allows us to recognize three regimes in the detonation drive of inert materials.
These are the:
1. momentum-dominated regime, for $M/C > 7$ and $v < 350$ m/s,
2. energy-dominated regime, where $0.3 < M/C < 7$ and $350$ m/s $< v < 2900$ m/s, and
3. gas-dynamics-dominated regime, for $M/C < 0.3$ and $V > 2900$ m/s

It has been shown by CTH wave-code calculations that use of a low-impedance "buffer" material between detonating explosive and a steel plate can increase the velocity to which the steel is driven. This pertains particularly for large values of $M/C$, and the effect diminishes to virtually nothing by $M/C = 1$. There can be a gain in driven velocity even when the intervening material is a laminate of high- and low-impedance materials. A caveat: This behavior would not be expected, however, if the low-impedance buffer material were a gas or an energy-absorbing, highly porous material.

ACKNOWLEDGMENT
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REFERENCES