

Shear Initiation from Low Velocity Impact

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ABSTRACT

Ignition and initiation by low velocity impact are usually investigated experimentally by the so-called Steven test. In this test a heavy steel projectile is launched against a steel sandwich target containing the tested explosive. The output is monitored by blast gauges three meters from the target. The test results are in terms of the threshold impact velocity for ignition, and of the TNT equivalent of the tested explosive as a function of impact velocity beyond this threshold. To date there is no accepted model that can predict the outcome of a Steven test or any other low velocity impact event. There is a great demand for such a model for explosive safety issues. In this paper we propose a model to predict the outcome of a low velocity impact event. The model is simple to use in a hydrocode, and goes over smoothly to shock initiation and detonation phases of the impact event. We calibrate the model from Steven test data, and we then use it to predict the propagation of the deflagration wave in a Steven test.

INTRODUCTION

Shock initiation of solid explosives is a well-established discipline. It is widely accepted that under shock, heterogeneous explosives develop initiation centers known as hot spots, which are mainly related to micron scale voids in the explosive. On the mesoscale, deflagration waves propagate out of those hot spots, transforming the reactant into products. This is the basis of modeling shock initiation as a two-stage process of ignition and growth [1,2]. There is a threshold for shock initiation resulting from activation of hot spots. But tests show that explosives may react even below that shock initiation threshold. For HMX based formulations for example, a reactive event may occur even at impact velocities of 30-50 m/s (low velocity impact), while the shock initiation threshold may be as high as 300-500 m/s. A low velocity impact event may or may not evolve into a detonation, and its main significance is in terms of safety. As low velocity impact cannot activate hot spots by a pore collapse mechanism, the energetic event that it may cause has to depend on some other mechanism. It is now widely accepted that this other mechanism has to do with heat localization at adiabatic shear bands (ASB) [3,4]. As ASB are created in regions of plastic (shear) flow, low velocity impact initiation may also be termed shear initiation.

Two questions are of importance regarding shear initiation. 1. what is the reaction threshold, and 2. once such a reaction starts, how does it propagate. At any specific situation, the second question includes several sub-questions, which are: does the reaction propagate or is it quenched; if it propagates, is it traveling at a constant velocity or is it accelerating; what is the level of violence of the over whole event. Partial answers to these questions are obtained experimentally by the so-called Steven test [5,6] (that replaced the so-called Susan test [7]), and also by several special purpose non-standard tests [8].

But it's impossible to extrapolate from tests to real situations without an appropriate model, and the modeling status of shear initiation is quite poor. Because ASB in PBXs are very thin (of the order of $1\text{ }\mu\text{m}$) [3], It's next to impossible to simulate shear initiation directly. A macroscopic model for shear initiation is therefore necessary, similar to pressure (hot spot) initiation models. Several threshold (or ignition) low velocity impact models can be found in the literature [9,10], but they're quite complex and seem somewhat arbitrary. In the past we proposed such an ignition model [11], that is based on direct experimental observations [4], and which we calibrated from Steven test data. We call it the PD ignition model, where P is pressure, D is the effective plastic strain rate, and where the reaction threshold is given in terms of the product of these two variables. But a model that predicts what may happen beyond such an ignition is still needed. Here we propose such a model which we call TDSR (Temperature Dependent Shear Reaction). Our TDSR model is constructed in the same form as our shock initiation model TDRR [1,2]. In this way we're able to use the two models simultaneously, and go over smoothly from shear initiation to shock initiation and then to detonation.

STEVEN TEST

In a Steven test [5,6] a steel projectile is launched towards a target containing the explosive to be tested. The cross-section of a Steven test is shown in Fig. 1.

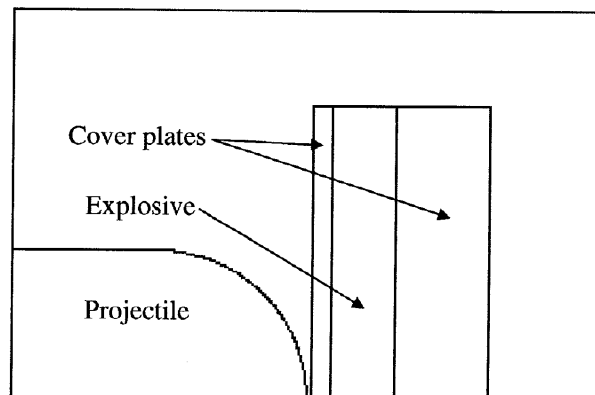


Figure 1. Layout of the Steven test.

The steel projectile is 60mm long and of a 60mm diameter, and has a spherical front of 30mm radius. The target is a disc with a diameter of 120mm. It consists of three layers: a 4mm steel front plate, a 14mm disc of the tested explosive, and a 19mm steel back plate. The diagnostics are blast gauges placed at a distance of 3m from the target. The test results are in terms of the maxima of the pressure pulses recorded by those gauges. An example of Steven test results taken from [5] is shown in Fig. 2.

We see from Fig. 2 that:

- For a given explosive material there's a threshold impact velocity V_{ig} , below which the explosive is not ignited and there's no reaction.
- Above V_{ig} , the blast maximum overpressure at the gauges increases approximately linearly with impact velocity.

A higher ignition velocity and a lower slope beyond the ignition velocity signify a less sensitive explosive to low velocity impact.

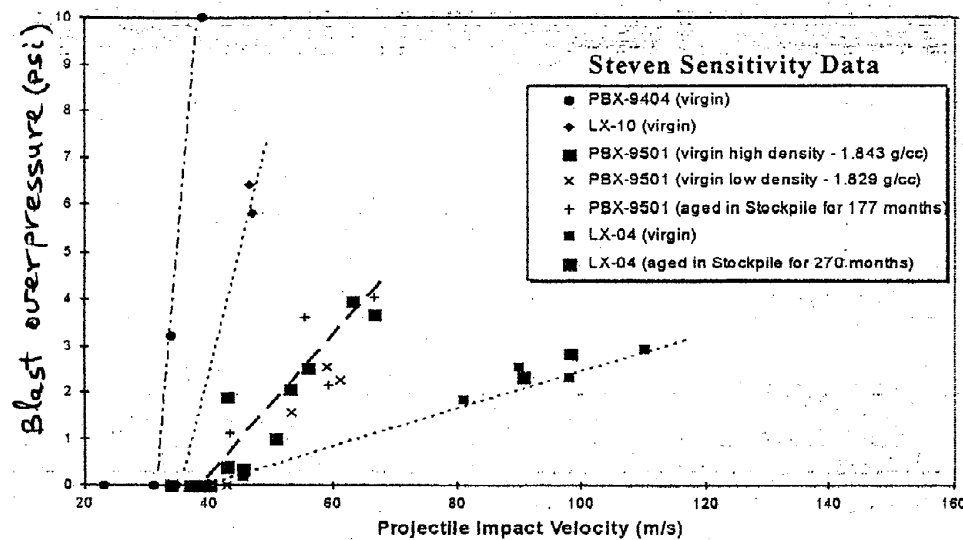


Figure 2. Steven test results taken from [5].

In [5] they calibrated the explosive equivalent strength in terms of the blast maximum overpressure it creates. Using this calibration for the data of the explosive LX-04 from Fig. 2, gives the data points in Fig. 3. We see from Fig. 3 that using the experimental straight-line result from Fig. 2, we get that the explosive energy equivalent as function of impact velocity is also a straight line. This is unlike the usual scaling of blast waves.

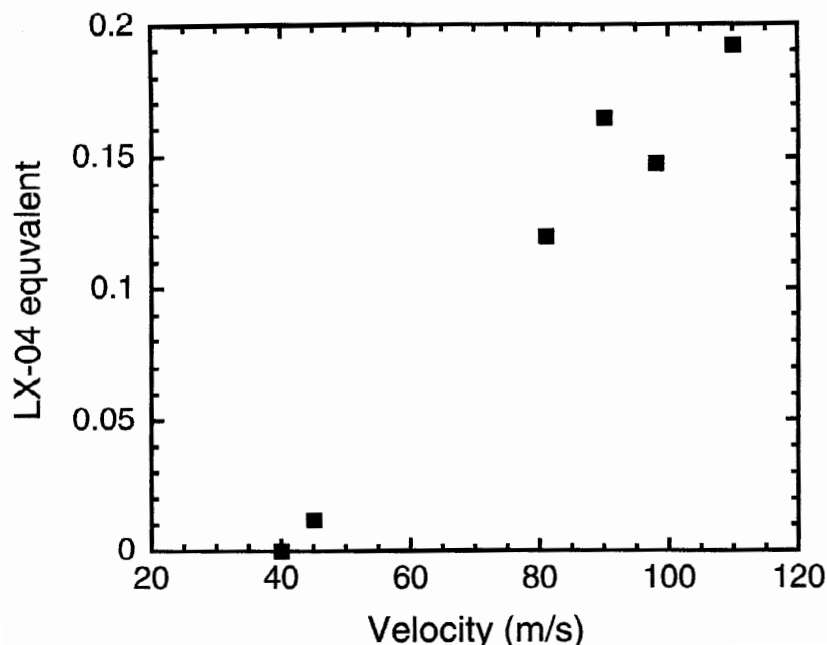


Figure 3. Steven test data for LX-04, in terms of explosive energy equivalent.

PD IGNITION MODEL

We first presented our low velocity impact PD ignition model in [11]. It's based on experiments described in [4]. Briefly, we assume there that ignition in a macroscopic computational cell depends on the value of the product PD, where P is the pressure and D is the effective plastic strain rate. In [11] we calibrated for LX-04 (85% HMX and 15% Viton) the value $(PD)_{ig}=0.0024\text{GPa}/\mu\text{s}$ at $V_{ig}=45\text{m/s}$. The calibration process is:

- Run a simulation of the Steven test at $V=V_{ig}$.
- At the end of each time step scan the computational mesh and look for the maximal value of PD, denoted by $(PD)_{max}$.
- At the end of the simulation plot the history of $(PD)_{max}$. The maximum of this history is the ignition value $(PD)_{ig}$.

Once calibrated, the PD model can be used to predict low velocity impact ignition for any other shape and impact configuration of the same explosive. This may be done as follows:

- Run a simulation for the explosive shape and impact configuration of interest.
- At the end of each time step scan the mesh and look for the maximal value of PD.

When the current maximal PD exceeds $(PD)_{max}$ there should be ignition at that time and at the maximal PD location.

SHEAR REACTION MODEL (TDSR)

As with our shock initiation model (TDRR), here too we assume that reaction rate depends on the temperature of the reactant. The two models have a similar dependence of the reaction rate on temperature, but they differ in terms of the reaction rate magnitude at the same temperature. The reaction rate of TDSR is much smaller, and its temperature threshold is much lower. For both cases (TDRR and TDSR) reaction rate is given by an Arrhenius like relation:

$$\dot{W} = y(W)R_T \exp(-T^*/T_s) ; \quad T_s > T_{ig} \quad (1)$$

where W is the reaction progress parameter (varies from 0 to 1), $\dot{W}$ is the reaction rate, $y(W)$ is the normalized burn topology function as given in [1], T_s is the temperature of the reactant, and R_T, T^* are material parameters to be adjusted from tests. Such a relation is usually described by an Arrhenius diagram. In Fig. 4 we show an example of an Arrhenius diagram for both pressure and shear reaction rates. We see from Fig. 4 that:

- The shear reaction threshold temperature is quite low (304K compared to 400K for pressure reaction).
- The slope T^* is lower (400K compared to 2000K)
- The amplitude R_T is much lower ($0.05/\mu\text{s}$ compared to $100/\mu\text{s}$).

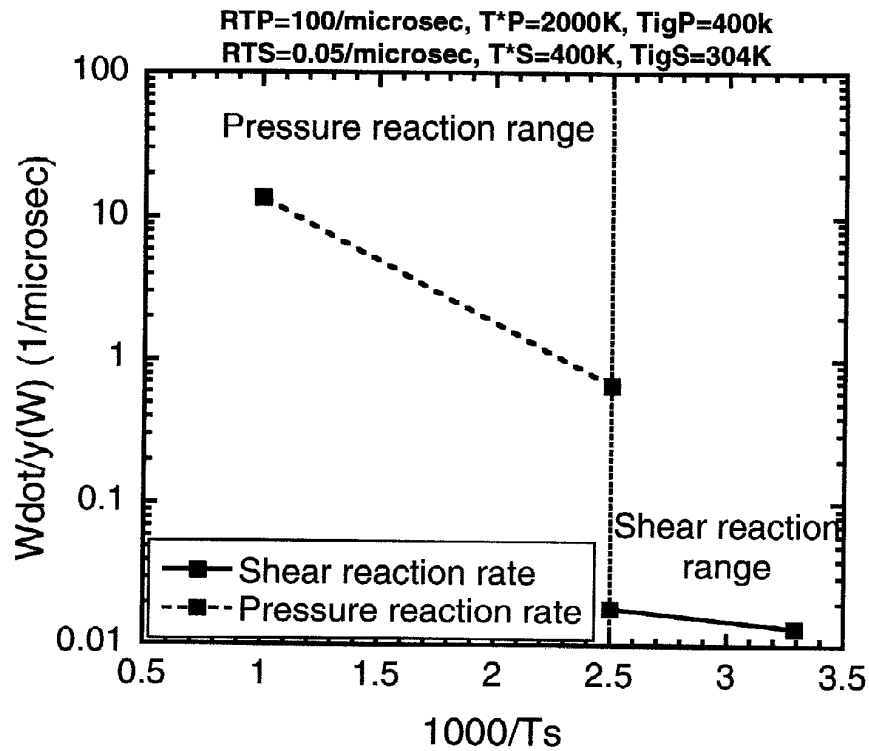


Figure 4. Arrhenius diagram for pressure reaction (TDRR) and shear reaction (TDSR).

We calibrate the parameters of the shear reaction rate from results of Steven tests:

- The threshold T_{ig} has to be compatible with the ignition velocity V_{ig} .
- The slope T^* has to be compatible with the slope in Fig. 3.
- Changing the amplitude R_T moves the line in Fig. 3 up and down.
- The value of R_T is determined so that the computed line falls on top of the experimental line.
- To demonstrate how this works we ran a hydrocode simulation of the Steven test with an ignition velocity of 100m/s. The reaction rate parameters are those given in Fig. 4. In Fig. 5 we show maps with lines of equal W in steps of 0.2 and for an impact velocity of 120m/s.

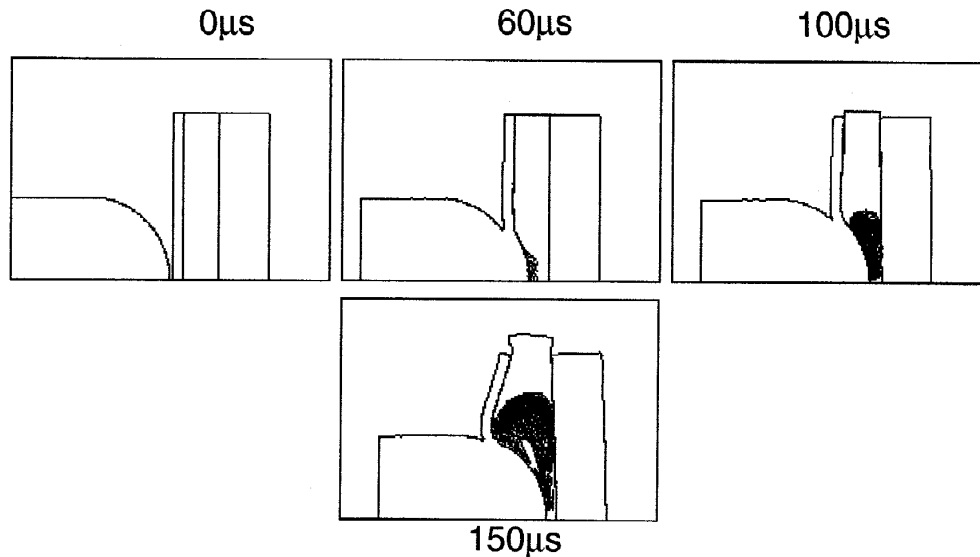


Figure 5. Simulation of a Steven test for an impact velocity of 120m/s.

Lines of equal W in steps of 0.2 (black area).

We see from Fig. 5 that:

- There's substantial noise (in terms of W) in the reacted area.
- The reaction front propagates at a velocity of about 200m/s.

In Fig. 6 we show histories of W averaged over the entire explosive disc for different impact velocities. This is the same as the explosive energy equivalent.

We see from Fig. 6 that the extent of reaction saturates after about 140μs. This is probably because of the release waves from the outer boundary.

In Fig. 7 we show the maxima of Fig. 6 as a function of the impact velocity.

We see from Fig. 7 that the straight line has a slope close to that obtained experimentally as shown in Fig. 3. This means that our TDSR model can be calibrated from Steven test data. We did not proceed to calibrate the TDSR parameters from data in the literature, as we prefer to have our own experimental data first.

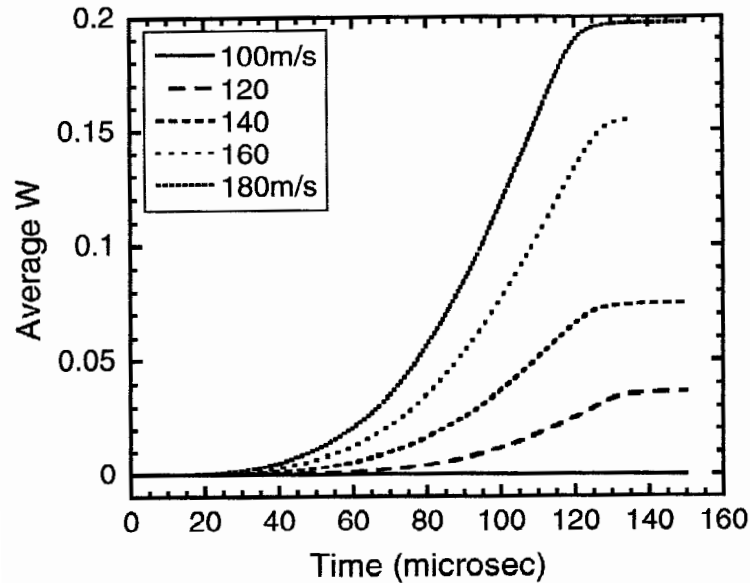


Figure 6. Average W histories (over the whole explosive disc) for different impact velocities.

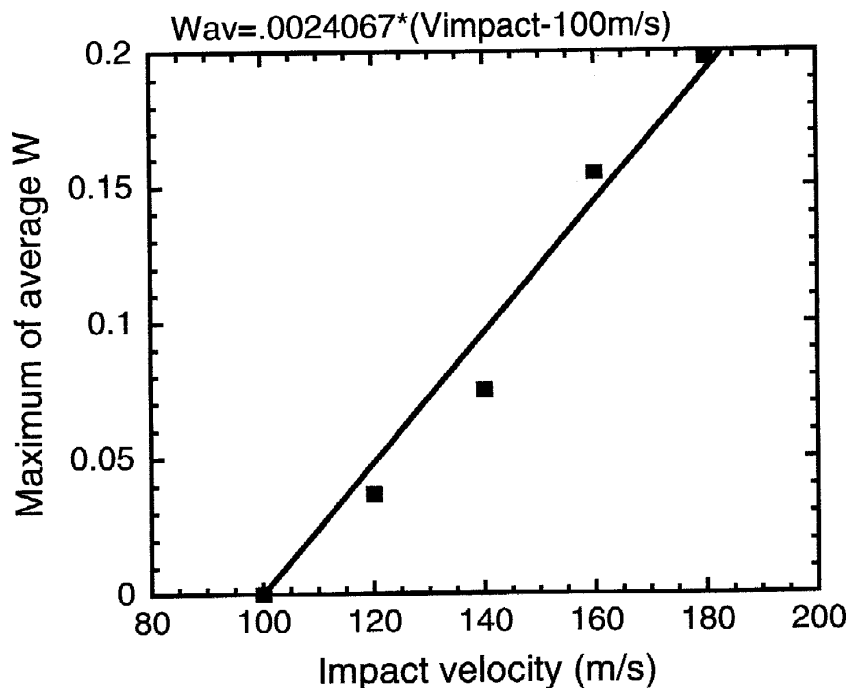


Figure 7. Maximum of average W (over the whole explosive disc) for different impact velocities.

SUMMARY

Low velocity impact of explosives is an impact configuration below the threshold of shock initiation. Low velocity impact may cause a slow energetic event that can evolve into shock initiation and detonation. Low velocity impact reaction, also termed shear initiation, is triggered by thermal localization at adiabatic shear bands.

We propose here a macroscopic model for shear reaction which we call Temperature Dependent Shear Reaction (TDSR). The model includes:

- A mechanical ignition threshold for shear reaction in terms of the product PD (P=pressure, D=effective plastic strain rate).
- A temperature dependent reaction rate that is structured similar to the reaction rate we use for shock initiation and detonation.
- A smooth transition from shear reaction to shock initiation and detonation.

We show how to calibrate the parameters of the TDSR reaction rate from Steven test data, and give an example of a Steven test simulation with an HMX based explosive.

References

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