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Desensitization by Pre-shocking in Heterogeneous Explosives and its Numerical Modelling

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Abstract: Desensitization caused by pre-shocking in heterogeneous explosives is discussed. The aim of this study was to find a simple numerical model that could reproduce the important features of previously reported shock desensitization experiments. After reviewing the previous experimental results and modelling efforts, an extension of the Lee-Tarver reactive flow model is proposed. The proposed desensitization model is based upon the experimentally determined desensitization criteria for explosives. The additional parameters required for this extension can be calibrated by experiment for a typical explosive. The new model has been implemented in the hydrodynamic code LS-DYNA as a user defined equation of state, and is now available to simulate various kinds of situations involving explosives up to the limits and capabilities of LS-DYNA. Desensitization by pre-shocking in double shock experiments, reflected shock and detonation quenching experiments have been studied using the new model, and the results were found to be in qualitative agreement with the experimental results reported in the literature.

Keywords: shock desensitization, desensitization criterion, ignition and growth, Lee-Tarver model, detonation quenching, reflected shock ignition, EDC37

1 Introduction

The term "shock desensitization" is usually referred to a variety of phenomena occurring in explosives such as dead pressing, detonation quenching and the reduced sensitivity of explosives to multiple shocks. It is now an established fact that passage of a weak shock desensitizes the explosive to a succeeding stronger shock. Although its chemical composition is almost unchanged by the first shock, the pre-compressed explosive requires a stronger shock for initiation compared to that required for initiation of the pristine, unshocked material. Usually a strong second shock does not cause reaction until it overtakes the first shock.

2 Experimental Evidence

The phenomenon of desensitization of heterogeneous explosives by pre-shocking has long been under investigation by many researchers. As early as 1960, Campbell *et al.* [1] reported that a 3.9 GPa preshock desensitized a plastic-bonded HMX explosive to initiation by a following 10 GPa shock. In a later study, Campbell and Travis [2] desensitized PBX-9404 and Composition B-3 by subjecting them to pre-shocks in the pressure range 1.0-2.4 GPa. It was observed that desensitization occurred in a very brief time window. Using their experimental data, a relation was proposed between the pre-shock pressure (P) and the time required (τ) for desensitization of PBX-9404 as:

$$P^{2.2}\tau = 1150 \text{ (kbar}^{2.2}\cdot\mu\text{s)} \tag{1}$$

Another study [3] of the initiation and build-up to detonation of Composition B covered by steel plates of different thicknesses and impacted by a shaped-charge jet, is also evidence for desensitization by pre-shocking. Using laser velocity interferometry, Setchell [4] investigated the effects of precursor shocks (3.2 GPa sustained shock of duration 3.7 μs or a 2.0 GPa ramp wave having a 0.6 μs rise time) propagating ahead of stronger 5.0 GPa shock waves in a granular low porosity PBX-9404 explosive. The extension of the run distance to detonation depended on the duration of the precursor shock wave in both cases.

Mulford *et al.* [5] studied the effect of a sustained shock followed 0.65 μs later by a second shock, on the initiation of PBX-9404. The run distance to detonation was extended and the initiation of detonation occurred nearly as anticipated by Pop-plots for PBX-9404, after the coalescence into a single wave of a 2.5 GPa pre-shock and a 5.6 GPa main shock. Slight growth of reaction was observed in the pre-shocked region on the passage of the second shock, indicating that the desensitization in the pre-shocked region was not perfect. This was in accordance with Equation 1, as in this case:

$$P^{2.2}\tau = 644 \text{ (kbar}^{2.2}\cdot\mu\text{s)} \tag{2}$$

which is less than the experimentally determined [2] value for PBX-9404.

Mulford and Swift [6] later developed a reactive flow model to reproduce the experimentally observed shock desensitization phenomenon.

Tarver *et al.* [7] observed the desensitization of LX-17 in reflected shock and colliding shock experiments, and numerically modelled this using the ignition and growth reactive flow model [8]. These pressure histories, measured by manganin pressure gauges, showed that LX-17 can be dead pressed at slightly lower pressures than the threshold (7 GPa).

Bordzilovskii and Karakhanov [9] experimentally studied multiple shock initiation of pressed RDX/paraffin and HMX/paraffin compounds and observed weak reaction behind the second shock wave. It was found that the run distance to detonation in the pre-shocked explosive was simply the sum of the distance at which the two shocks coalesced and the run to detonation distance expected for the second shock wave from Pop-plot data. The experimental work by Bat'kov *et al.* [10] also reveals the decrease in shock-wave sensitivity of pressed TNT and TNT/RDX compositions (50/50 and 30/70) caused by pre-shocking.

More recently, Vandersall *et al.* [11] performed shock desensitization and detonation quenching experiments on LX-17 using a Teflon™ flyer fired from a gas gun to impact one end of a cylindrical sample of LX-17 and to generate a single low amplitude shock wave to pre-shock the explosive sample just prior to detonating it from the other end. At pre-shock pressures of ~0.68 and ~1.1 GPa, LX-17 detonation waves failed in the pre-shocked region, a process referred to as detonation quenching. However, at a pre-shock pressure of ~0.52 GPa, the detonation wave proceeded through the sample, and no detonation quenching was observed. It was concluded that the lower limit for the desensitization shock strength lies between 0.52 to 0.68 GPa. However more experiments are needed to determine exactly the limits of the pressure range and the time window for desensitization.

A series of double shock initiation experiments [12, 13] on an HMX-based explosive EDC37 (91% HMX and 9% binder) revealed more interesting facts. In the first set of experiments (experimental shots 1175/1176), the explosive was subjected to a 2.87 GPa shock followed by a 6.2 GPa shock. No reaction was observed in the first wave, and the run to detonation distance after the waves coalesced was as expected from the single shock Pop-plot. However in the second set of experiments (shots 1194/1195), where the explosive was subjected to a 3.92 GPa shock followed by a main shock of 8.56 GPa strength, significant reaction occurred in the first wave and even more in the second wave. The run distance to detonation after the waves coalescenced was also less than that expected from the single shock Pop-plot data. The results of experimental shots 1281/1282 were also similar to the second set, however the detonation occurred approximately at the point of coalescence of the two waves. These results indicate that the often quoted ‘rule of thumb’, that build-up to detonation in doubly shocked explosive does not start until the waves coalesce [2], no longer applies in the situation where first shock generates significant hot-spot reaction.

Mader [14] reported that Dick imposed pre-shocks of 2.3 and 5.0 GPa respectively on PBX-9502 explosive. In both cases, the detonation failed to propagate in the pre-shocked explosive. The pre-shock pressures were below the ignition threshold for PBX-9502. These results suggest that the desensitization occurred by mechanically compressing out the potential hot-spot sites, rather than by partial chemical reactions.

3 Modelling Efforts

Although some physics-based shock initiation models [15-17] have been reported to account for the desensitization phenomena, these models require huge computation resources. On the other hand, most of the phenomenological reactive flow models are incapable of simulating the desensitization induced by pre-shocking. Many attempts to include the desensitization effect in these models have been reported in the literature. The JTF model [18] accounts for this effect by restricting the creation of hot spots to the first shock only, and allowing a second shock to provide only adiabatic heating. The Wescott-Stewart-Davis (WSD) model [19] has been improved [20] to a temperature dependent form WSD (T). Although WSD (T) in the current form is incapable of predicting global desensitization, it is capable of predicting the reduction in the reactivity of the explosive with multi-shock compression. Mader used the multiple shock Forest-Fire model [21] to simulate the shock desensitization of Composition B resulting from the bow shock in metal jet penetration experiments [22]. Aminov *et al.* [23] developed a kinetic model, based on the activation energy of hot spots, to simulate the double-shock experiments [7] for LX-17 explosive. It was stated that the model described represented experiments not “worse” than the Lee-Tarver model. The CREST model [24] has been reported recently to predict desensitization phenomena [25], however, the model is still being improved upon at the Atomic Weapons Establishment (AWE), UK [26].

The standard ignition and growth Lee-Tarver model [27] is also incapable of predicting the desensitization effect by precursor shocks, since there is no mechanism to differentiate between a single and a double shock process. In this paper we focus on an adaptation of the Lee-Tarver ignition and growth model for simulation of desensitization in explosives.

3.1 Adapting the Lee-Tarver model

The Lee-Tarver model employs separate temperature-dependent JWL equations of state (EOS) for both the unreacted explosive and the reaction products, and a reaction rate equation. The three term reaction rate equation for the standard model is of the form:

$$\dot{\lambda} = R_I + R_{G_1} + R_{G_2},$$

where

$$R_I = I(1-\lambda)^b\,(\eta - 1 - a)^x \times H(\lambda_{ig\max} - \lambda) \tag{3}$$

$$R_{G_1} = G_1(1-\lambda)^c\,\lambda^d\,p^y \times H(\lambda_{G_1\max} - \lambda)$$

$$R_{G_2} = G_2(1-\lambda)^e\,\lambda^g\,p^z \times H(\lambda - \lambda_{G_2\min})$$

and H is a Heaviside function (equals one when the argument is positive, otherwise zero). The dot over λ denotes its time derivative.

The standard Equation 3 does not account for dead pressing and thus results in the rapid reaction by a second shock. Several attempts have been made, all on *ad hoc* bases, to modify the Lee-Tarver ignition and growth model in order to reproduce the main features of some particular experiments.

Long ago, Tarver *et al.* [7] added a condition in the reaction rate equation to account for the desensitization of LX-17 by reflected shock. The condition was that if a critical range of pressures were applied to the explosive, the reaction rate was forced to zero. The calculated growth histories using the modified reaction rate equation agreed well for the reflected shock experiments, except for a few exceptions.

Whitworth *et al.* [28] described a simple model to predict the shock desensitization effect by modifying the reaction rate equation, making it dependent on the pre-shock pressure P_{shk}. In place of the local pressure P in the reaction rate equation, $P = min\ (P, P_{shk})$ was used to find the reaction rate. A qualitative agreement was reported for the calculations of Mulford's precursor shock experiment [5] using the modified reaction rate equation. Whitworth also applied his modified reaction rate equation for detonation quenching experiments. However, contrary to the experimental results [2], the rate of quenching increased with decreasing pressure of the precursor shock.

In order to model the qualitative features of the corner-turning failure in LX-17, Souers *et al.* [29] presented a failure model that cut off the reaction rate below certain detonation velocities. A single reaction rate equation was used, which was a stripped down version of the Lee-Tarver ignition and growth model, and the coefficients of this rate equation were different in different regions of the explosive. In a more recent approach, Souers *et al.* [30] later refined his model by employing a single reaction rate format, which varied for different pressure regimes in the explosive to simultaneously model dead zone, failure region and the detonation region in corner turning experiments. This model could reproduce various experimental features, including the detonation failure region in the corner turning experiments of LX-17.

DeOliveira *et al.* [31] proposed a modification in the Lee-Tarver ignition and growth model by introducing the desensitization rate S as:

$$S = MP(1 - \varphi)(\varphi + \varepsilon) \tag{4}$$

where φ is the degree of desensitization, which varies from 0 to 1. At $\varphi = 0$, the material is in the normal or virgin state while $\varphi = 1$ represents the completely desensitized explosive. M is the rate constant and ε is a small positive number to ensure some desensitization at $\varphi = 0$ when $P > 0$.

The critical compression in the ignition term of the original Lee-Tarver model is also prescribed as a function of φ. Thus the ignition term in reaction rate Equation 3 becomes:

$$R_I = I(1 - \lambda)^b\, (\eta - 1 - a(\varphi))^x \times H(\lambda - \lambda_{ig\max}) \tag{5}$$

where the modified critical compression $a(\varphi)$ is defined as:

$$a(\varphi) = a_0(1 - \varphi) + a_1(\varphi), \tag{6}$$

where $1 + a_0$ is the critical compression for ignition of the virgin material and $1 + a_1$ is that for the completely desensitized material. The second change in the reaction rate equation proposed [31] was to change the switching limit of the growth term from 0 to $\lambda_{G_1\max}(\varphi)$, defined by $\lambda_{G_1\min} = \lambda_c\, \varphi$, where $\lambda_c > 0$. Thus the modified growth term $R_{G_1,\varphi}$ for the desensitized explosive is defined as:

$$R_{G_1,\varphi} = G_1(1 - \lambda)^c\, \lambda^d\, p^y \times H(\lambda - \lambda_{G_1\min}(\varphi))\, H(\lambda_{G_1\max} - \lambda) \tag{7}$$

This modification requires four additional empirical constants to enable the ignition and growth model to account for the desensitization effect. Using the augmented model, DeOliveira *et al.* [31] qualitatively reproduced the main features of the corner turning experiments including the dead zones. It has been used by Tarver [32] for simulation of corner turning experiments, Jack-Rabbit experiments and detonation diffraction experiments [33].

The form factor $(1-\varphi)\varphi$ for the desensitization rate equation (Equation 4) seems similar to the form factor $(1-\lambda)^c\,\lambda^d$ of the growth terms in the original Lee-Tarver reaction rate equation, with λ replaced by φ. However, we find no logic behind this similarity. The form factor $(1-\lambda)^c\,\lambda^d$ in the growth terms of the Lee-Tarver reaction rate equations not only forces the growth rate to zero at the start and end of the reaction but also corresponds to the inward and outward burning of the pores, and the exponents are set to match the calculation results with the results of the shock to detonation transition (SDT) experiments. While in the desensitization reaction rate equation, the form factor $(1-\varphi)\varphi$ is just meant to force the desensitization rate to zero at the start and at the end of the desensitization process. As the desensitization is assumed to be mainly caused by the collapsing of pores, and there is no reason to believe that the collapsing rate of the pores is lowest when the maximum number of pores is available at the start. Moreover, as shown in Figure 1, the form factor is maximum when the material is 50% desensitized, which implies that the desensitization rate is also maximum when the material is 50% desensitized.

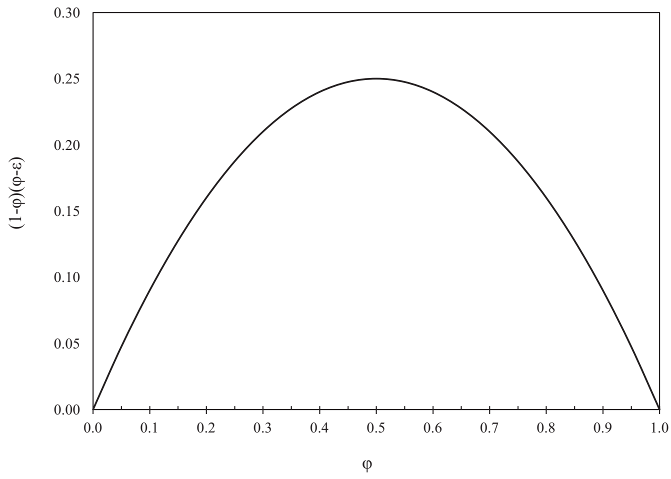

Figure 1. The form factor for the desensitization model proposed by DeOliveira [31].

Another issue with the desensitization rate is its linear dependence on the pre-shock pressure. Using their experimental data, Campbell and Travis [2] proposed a relation indicating that PBX9404 would be fully desensitized for $P^{2.2}\tau = 1150$ ($\text{kbar}^{2.2}\cdot\mu\text{s}$), where P is the pre-shock pressure and τ is the time required for desensitization. This implies that the desensitization rate is proportional to the 2.2 power of P, and not linearly proportional to P.

The method of finding the parameters of the DeOliveira's model is also described in reference [31]. DeOliveira guessed the values of the parameters ε and M. The parameter ε was assumed to be 0.0001 to yield a non-zero desensitization rate at the start of the desensitization process when ($\varphi = 0$). In addition, M was guessed to be 1000 to simulate the corner turning experiments. Later on Tarver [32] used $M = 1000$ to simulate the Jack-Rabbit experiments and the detonation diffraction experiments. However, Tarver [32] observed that the desensitization rate was actually higher than predicted by the calculations using the above desensitization model with $M = 1000$. However in gas gun experiments by Vandersall *et al*. [11], it was found that M should be increased from 1000 to 1200, eventually increasing the desensitization rate, to reproduce the experimental pressure history at various gauge points.

3.2 The present approach

In continuation of the effort in adapting the ignition and growth model for the shock desensitization problem, we followed DeOliveira's approach with a few changes. Our model assumes that the shock desensitization takes place when the pre-shock pressure is in a specific range for the explosive. For example, Wescott *et al*. [34] proposed that desensitization of PBX-9502 explosive takes place between around 1 and 6 GPa. We also assume that shock desensitization is a time dependent process, which is an experimentally established fact as discussed in the previous section. We also utilize the $P^m\tau$ criterion ($m = 2.2$ for PBX-9404 explosive) suggested by Campbell and Travis [2] to measure the degree of desensitization.

Firstly, we define the degree of desensitization φ as:

$$\varphi = \frac{1}{P^m \tau} \int_{t_1}^{t} P^m(t)\, dt \tag{8}$$

where the time t_1 corresponds to the pressure P_1 (the Hugoniot elastic limit, below which it is assumed that no damage is done to the explosive and after which the desensitization begins) and the upper limit of the above integral is time t, corresponding to the pressure P_2 (the threshold pressure for ignition). At $P = P_1$, $\varphi = 0$ and at $P = P_2$, $\varphi = 1$.

The degree of desensitization increases with pressure, as in Equation 8, and the desensitization rate also increases (Figure 2). However, it is suggested that although the desensitization increases with pressure, the desensitization rate decreases with increase in pressure in the specific interval (P_1, P_2). Therefore, we modified slightly the degree of desensitization determined by Equation 8 as follows:

$$\phi = \sin\left(\frac{\pi}{2}\varphi^n\right) \tag{9}$$

Exponent n can be used to adjust the rate of desensitization with pressure. The modified degree of desensitization ϕ (with $n = 0.5$) was used in our calculations. ϕ also varies, in a similar manner to φ, *i.e.* at $P = P_1$, $\phi = 0$ and at $P = P_2$, $\phi = 1$. However the rate of desensitization decreases with increase in pressure (Figure 2).

Secondly, the critical compression is increased to account for the loss of the potential hot spot generation sites, and is defined as:

$$a(\varphi) = a + \phi C_I, \tag{10}$$

where a is the critical compression of the virgin and the pre-shocked material and C_I is an empirical constant adjusted to inhibit the ignition term in the reaction rate equation (hence inhibiting the detonation in the pre-shocked explosive).

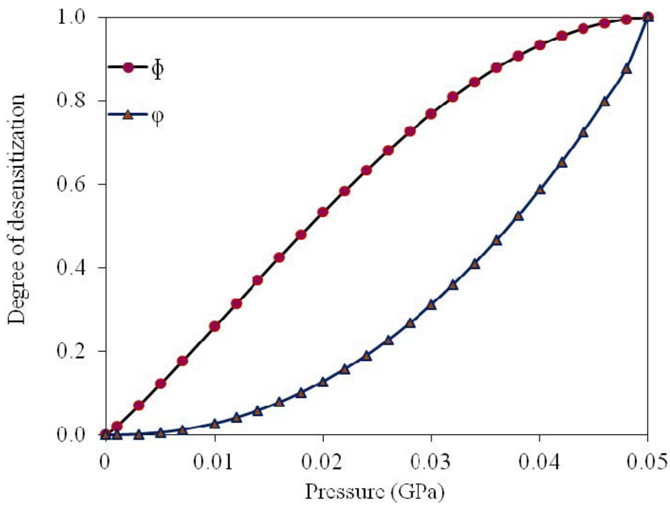

Figure 2. The degree of desensitization as a function of shock pressure calculated using two kinds of functions as given in Equations 8 and 9.

The growth term coefficients were also adjusted to control the growth of the reaction in the desensitized or partially desensitized explosive, as follows:

$$G_1(\varphi) = (1 - \phi)G_1, \\ G_2(\varphi) = (1 - \phi)G_2 \tag{11}$$

It should be noticed that if the explosive is partially desensitized ($\phi < 1$) by the first shock, it would be possible to have some reaction on the passage of the higher-pressure (second) shock. This feature helped us to reproduce the experimental results of the EDC37 double shock experiments [12, 13], as will be described in the next section.

The parameter C_I is the control parameter for the augmented/adapted model; its value for a typical explosive can be estimated by empirically fitting the experimental data. In our calculations involving PBX-9404, we estimated C_I to be 0.1.

4 Modelling and Simulation

The proposed extension was implemented in LS-DYNA to study the shock desensitization experiments.

4.1 Implementation in LS-DYNA

The Lee-Tarver ignition and growth model is one of the popular reactive burn models in use today and has been embedded already in various commercial hydrocodes, such as LS-DYNA, ANSYS AUTODYN, Abaqus and many others. By utilising the user equation of state option [35], we have implemented the ignition and growth model in LS-DYNA for the present study. First of all we have validated the newly implemented Lee-Tarver model by comparing the simulation results for simple problems using both the inbuilt and the newly implemented Lee-Tarver model. After validation, we modified the model as described in the previous section to simulate the double shock experiments. The degree of desensitization was stored as a history variable for every computational element and was updated after every time interval. During the execution of the subroutine, it is determined initially whether the input pressure (P) lies in the range for desensitization ($P_1 < P < P_2$). If so, then the degree of desensitization is determined using Equations 8 and 9, and stored in the history. When the second wave arrives, the modified parameters determined by Equations 10 and 11 are used to calculate the reaction rate using Equation 3.

Following implementation, this model can now be used as an equation of state for any explosive, to simulate a variety of situations involving explosives in the simulation environment of LS-DYNA. The new parameters P_1, P_2, m, $P^m\tau$ and C_I need to be defined along with other Lee-Tarver equation of state parameters in the input file. By setting the value of C_I to zero, the newly modified Lee-Tarver model functions as the traditional Lee-Tarver Model.

4.2 Simulation of double shock experiments

The schematic diagram for the simulation setup is given in Figure 3. A three-dimensional mesh with constraints applied on the lateral dimensions (along the x- and y-axes) was used. The mesh resolution was 20 elements per mm. The length of the explosive was taken as 20 mm. The pressure history was measured at various gauge points inside the explosive; the gauges were 0.5 mm apart. The series of double shock initiation experiments [12, 13] on an HMX based explosive EDC37 was chosen for the simulation and validation of the newly implemented model, because these experiments reveal a broader range of features involved in the shock desensitization process of an explosive. Figures 10 and 11 in reference [13] are experimental particle velocity histories at different gauge positions inside the EDC37 explosive for shots 1175/76 and shots 1191/92 respectively. For simulation of these reported experiments [13], two pressure pulses, where the second pressure pulse was delayed by the experimental time for each shot, were applied on one side of the explosive as initial conditions, as shown in Figure 3. Since the $P^m\tau$ criterion for EDC37 was not available, we used another HMX-based explosive (PBX-9404) instead. The use of PBX-9404 in place of EDC37 in the simulation is not expected to harm the qualitative nature of the results, since our purpose here is just to verify the availability of the model for simulating double shock experiments. Moreover, the HMX contents in the two explosives are similar (94% and 91% in PBX-9404 and EDC37, respectively). For the same density of the two explosives, some authors [36, 37] have used the same reaction products JWL equation of state for both explosives. The detonation velocities of the two explosives are also similar. The parameter set for the Lee-Tarver model of PBX-9404 with a two-term reaction rate equation was taken from LLNL report [38] and is reproduced in Table 1.

Table 1. Physical properties and parameters for the augmented Lee-Tarver model

Physical properties		Density [g/cm^3]	1.842
		C_v products [Mbar/K]	1.0E-5
		C_v reactants [Mbar/K]	2.7813E-5
		Shear Modulus [Mbar]	0.045
		Temperature [K]	298
Reactants JWL EOS parameters		A [Mbar]	9522
		B [Mbar]	−0.05944
		R_1	14.1
		R_2	1.41
		Ω	0.3
Product JWL EOS parameters		A [Mbar]	8.524
		B [Mbar]	0.1802
		R_1	4.6
		R_2	1.3
		Ω	0.38
Reaction rates	Ignition term	parameter I [μs^{-1}]	44
		reaction ratio exp.	0.222
		critical compression. a	0.01
		compression exp. x	4.0
	First growth term	G_1 [Mbar^{-y}μs^{-1}]	0
		reaction ratio exp. c	0
		reaction ratio exp. d	0
		pressure exp. y	0
	Second growth term	G_2 [Mbar^{-z}μs^{-1}]	495
		reaction ratio exp. e	0.222
		reaction ratio exp. g	0.667
		pressure exp. z	2.0
	Limits	λ_{igmax}	0.3
		λ_{G1max}	1
		λ_{G2min}	0
Augmented model parameters		P_1 [Mbar]	0.01
		P_2 [Mbar]	0.05
		M	2.2
		$P^m\tau$ [Mbar$^{2.2}$·μs] [2]	2.864E-4
		C_I	0.10

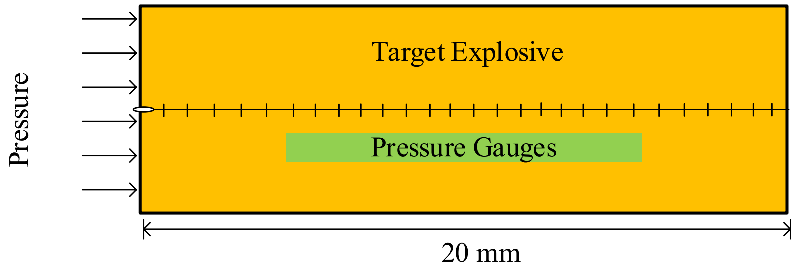

Figure 3. Simulation setup for double shock studies.

The simulation results are plotted in Figures 4 and 5 and in Figures 6 and 7 for the original and modified Lee-Tarver models (for shots 1175 and 1191 [12, 13] respectively). The comparison between the presently calculated and the experimental run distance to detonation for the three experimental shots is given in Table 2 below.

Table 2. The calculated and experimental results of double shock experimental details for shots 1175, 1194 and 1281

Shot	First shock pressure [GPa]	Time between shocks [μs]	Second shock pressure [GPa]	Coalescence distance [mm]	Detonation run distance [mm]			
					From front face		From coalescence	
					calculated	experimental	calculated	experimental
1175	2.94	0.550	6.2	5.0	11.96	11.5	6.18	6.5
1194	3.93	0.676	8.54	4.5	9.43	8.0	2.43	3.5
1281	4.15	1.014	9.06	9.5	10	10	< 1	0.5

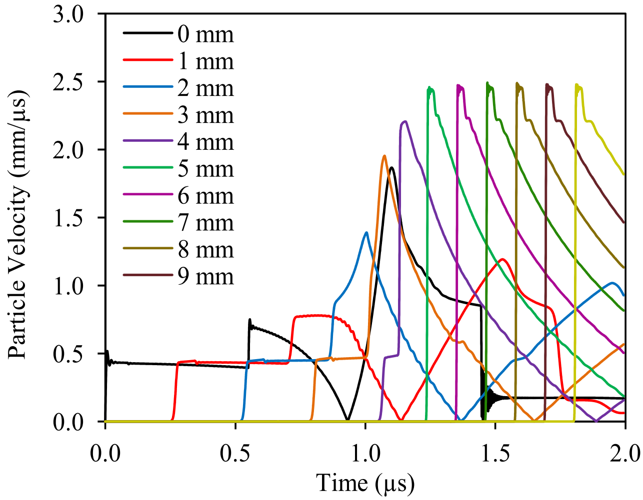

Figure 4. Particle velocity history plots calculated by the Lee-Tarver model for double shock experiments at different gauge positions inside EDC37 explosive for shots 1175/1176.

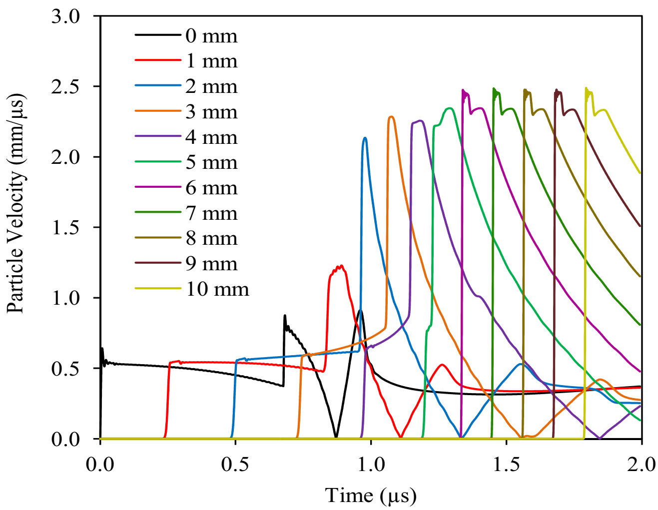

Figure 5. Particle velocity history plots calculated by the Lee-Tarver model for double shock experiments at different gauge positions inside the EDC37 explosive for shots 1194/1195.

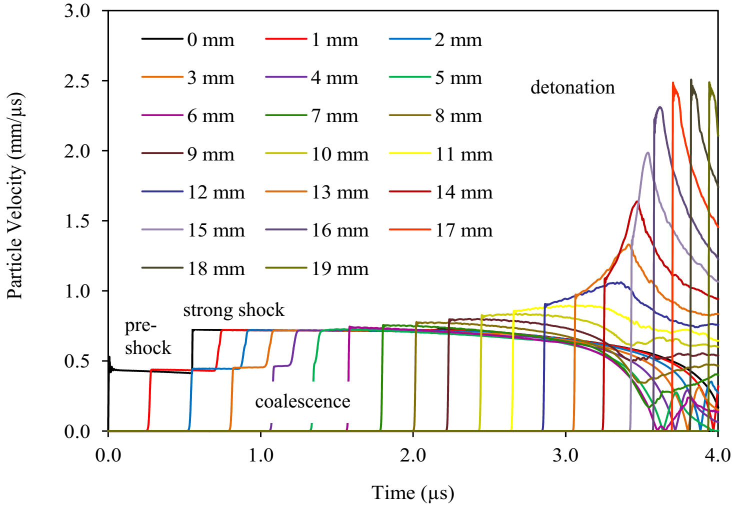

Figure 6. Particle velocity history plots calculated by the augmented Lee-Tarver model for double shock experiments at different gauge positions inside the EDC37 explosive for shots 1175/1176.

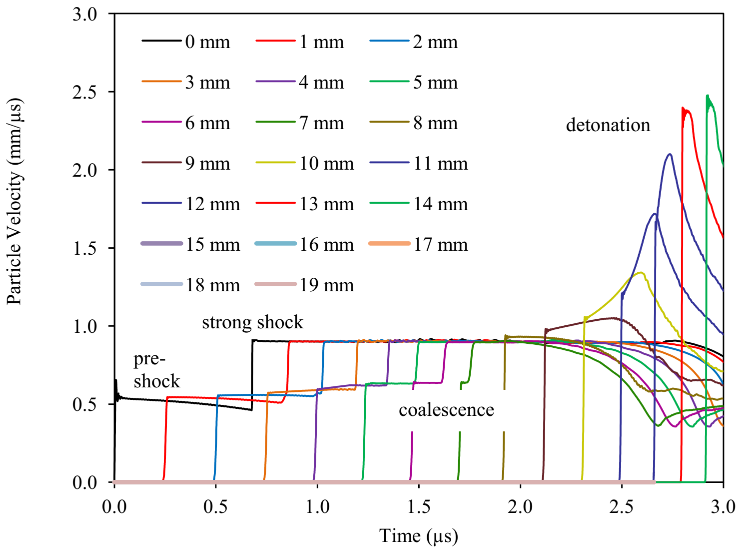

Figure 7. Particle velocity history plots calculated by the augmented Lee-Tarver model for double shock experiments at different gauge positions inside the EDC37 explosive for shots 1194/1195.

4.3 Reflected shock experiments

Tarver *et al.* [7] performed reflected shock experiments to study the response of LX-17 explosive. However for our calculations of reflected shock experiments, we used PBX-9404, again because the desensitization criterion for LX-17 was not available. Our aim here was to verify whether the augmented Lee-Tarver model is able to qualitatively reproduce the main features of the reflected shock experiments.

We modelled the problem by using a one-dimensional mesh of 20 mm length (Figure 8). The meshing details are the same as in Section 4.2. A sustained pressure pulse (3.93 GPa) was applied at one side of the explosive, being insufficient to cause detonation in the 20 mm length of the explosive. At the other edge of the mesh a perfectly reflecting boundary was applied. A high pressure (15.45 GPa) was caused by the reflection of the shock from the perfectly reflecting boundary.

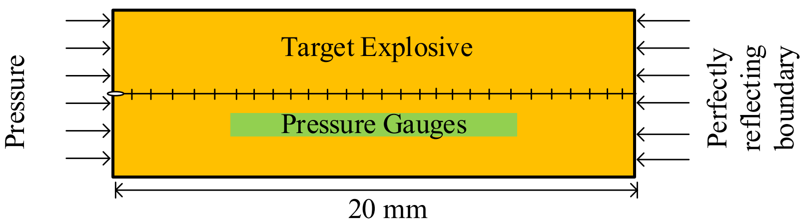

Figure 8. Simulation setup for reflected shock studies.

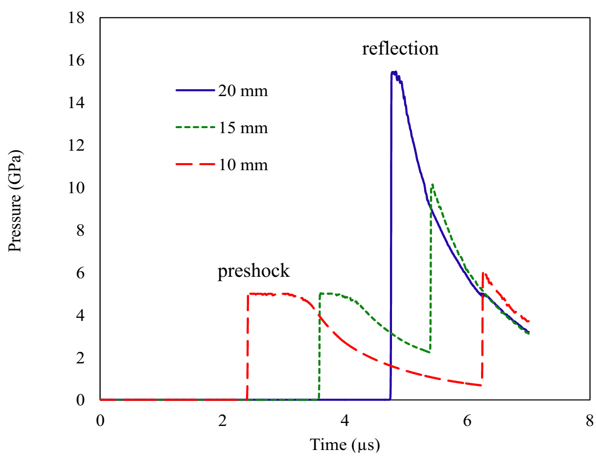

Figure 9. Pressure history at 3 gauge points inside the explosive at 10.0, 15.0 and 20.0 mm, respectively.

The pressure history at 3 gauge points inside the explosive, at 10.0, 15.0 and 20 mm respectively (the 20 mm gauge was at the highest pressure peak, while the 10.0 mm gauge was at the lowest peak) is shown in Figure 9.

4.4 Detonation quenching

Although the detonation quenching experiments were performed with LX-17, we used PBX-9404, again because the desensitization criterion for LX-17 was not available. We modelled the problem by using a one-dimensional mesh of 20 mm length (Figure 10). The meshing details are as described earlier. A sustained pressure pulse (3.0 GPa) was applied at one side of the explosive. This is insufficient to cause detonation in the 20 mm of the explosive. After a delay of 2.5 μs, 9.0 GPa pressure was applied as another boundary condition at the other edge of the mesh.

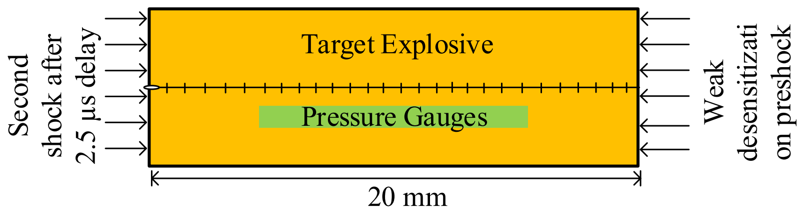

Figure 10. Simulation setup for detonation quenching studies.

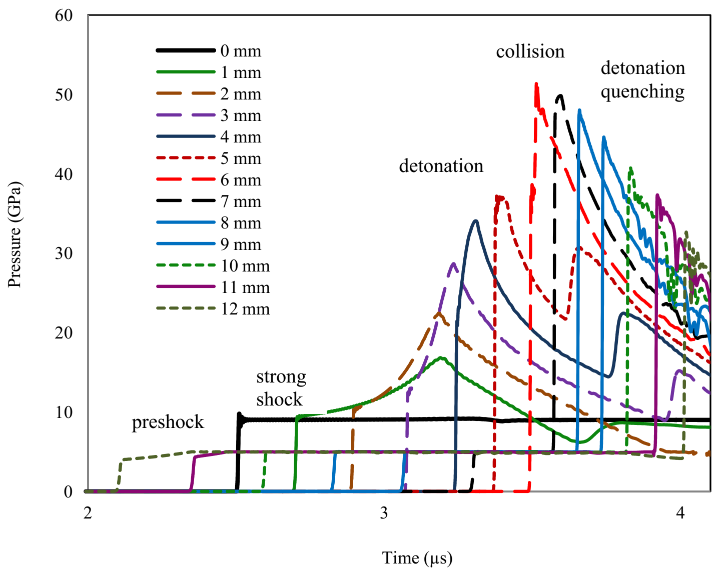

Figure 11. Pressure history at different gauge points inside the explosive.

The pressure history at various gauge points inside the explosive is shown in Figure 11, where the collision of the weak shock with the detonation wave is observed at the 6 mm gauge, after which the detonation wave was quenched, as can be observed by the continuously decreasing magnitude of the pressure peaks at the later gauge points.

5 Results and Discussion

As can be noticed from the experimental particle velocity plots for the shots 1175/76 given in Figure 10 in reference [13], no reaction is observed in the first wave, and the run distance to detonation after wave coalescence is as expected from the single shock Pop-plot for EDC37 (Figure 34 in [13]). However in the second set of experiments (shots #1191/92, plotted in Figure 11 in [13]), where the explosive was subjected to a 3.92 GPa shock followed 0.6 μs later by a main shock of 8.56 GPa strength, significant reaction occurred in the first wave and even more in the second wave. The run distance to detonation after wave coalescence was also smaller than that expected from the single shock Pop-plot data. The third set of experiments (shots 12881/2, plotted in Figure 12 in [13]) is similar to shots #1194/95 with slightly higher pressure and a greater time interval between the two shocks, the detonation occurred close to wave coalescence. The general principle, as formulated by Davis [39], states that the run distance to detonation (L) is defined as $L=x_0+r_{dd}$, where x_0 is the distance at which the waves coalesce and r_{dd} is the run distance to detonation for a single shock in the virgin explosive. The results indicate that this rule no longer applies in the situation where the first shock generates significant hot-spot reaction. The simulation results shown in Figures 6 and 7 are in accordance with this conclusion. The Lee-Tarver model has been modified to account for the desensitization effects. The results of the experiment [13] have been reproduced by using the modified Lee-Tarver model for the first time, at least qualitatively. This is an improvement on DeOliveira's approach used to simulate the same experiment [40]. The calculated run distance to detonation is also comparable with the experimental results. The original Lee-Tarver model is not capable of reproducing the desensitization effects in an explosive, as can be seen in Figure 4 and in Figure 5, which are the plots for the simulation of the experimental shots 1175 and 1194 respectively using the original Lee-Tarver model. The results obtained after modification of the model (plotted in Figures 6 and 7 for the two shots, respectively) are qualitatively in good agreement with the experimental curves (Figures 10 and 11 in [13]).

The new model was also used to simulate reflected shock experiments. The results (Figure 9) are in accordance with the trend observed in experiments that the reflected high pressure shock (14.5 GPa in this case) fails to detonate the explosive because it was desensitized by the earlier 3.93 GPa shock. The pressure histories at various gauge points show that the pressure keeps on decreasing with the passage of the reflected shock, and the highest pressure is noted close to the reflecting surface. It should be noted that the pressure at the reflecting boundary (at the 20 mm gauge) is not merely double the incident pressure, as one might guess from a non-reacting shock travelling in the explosive being reflected from a perfectly reflecting boundary. The weak shock near the reflecting boundary did not have sufficient time to completely desensitize the explosive. Since the desensitization model used here is based on the desensitization criterion, which is a function of both pressure and time, the degree of desensitization is a minimum near the reflecting boundary, and keeps on increasing with distance from the reflecting boundary. Therefore, some reaction occurs at the boundary, eventually increasing the pressure. However, the pressure drops as the shock travels away from the boundary because the degree of desensitization increases, resulting in a decrease in the reaction. This in accordance with the experimental results presented by Tarver *et al.* [7]. As discussed above, Tarver used a 20 mm thick LX-17 disc that was impacted by different types of flyer. The pressure histories were measure at 5, 10 and 15 mm depths. The pressure measured at the 15 mm depth was approximately double the incident pre-shock pressure. Obviously, the pressure at the reflecting surface at 20 mm depth would have been higher than at 15 mm depth. As shown in Figure 11, the present model also yields approximately double the pressure at the 15 mm depth.

Another test for the new model is the simulation of detonation quenching in shock colliding experiments. It is obvious from the results shown in Figure 11 that the fully developed detonation is extinguished when it enters the pre-compressed (dead) explosive which was earlier desensitized by a weak (3.93 GPa) shock. The pressure histories at various gauge points prove that the pressure continuously decreases in the direction of the detonation wave propagation after the shocks collide with each other. The highest pressure is at the point of collision of the waves.

6 Conclusions

The present modification of the Lee-Tarver model can be used to account for the desensitization effects. The results of the experiment [13] have been reproduced, at least qualitatively, by using the modified Lee-Tarver model. The run distance to detonation is also comparable to the experimental results.

The model proposed here is also based on the degree of desensitization, which is calculated on the basis of the $P^m\tau$ criterion which has been determined for some explosives by double shock initiation experiments [2]. After implementation in LS DYNA, this model is available to study a variety of problems involving explosives, especially desensitization by pre-shocking. Our model qualitatively reproduces the experimental results of EDC37 double shock experiments [12, 13]. The simulation results presented here successfully reproduce the main features of the desensitization of heterogeneous explosives by double shock, reflected shock and detonation quenching processes respectively, and provide qualitative agreement with the experimental results. The extension does not change the functionality of the original Lee-Tarver model, unless the explosive is subjected to a weak pre-shock, which desensitizes the explosive. Nor does it change the ignition and growth parameters of an explosive, except that a few more empirical constants have to be added to simulate the desensitization of the explosive.

The desensitization criterion for other heterogeneous explosives needs to be determined for further verification and calibration of the model for those explosives. Further desensitization experiments will be of extreme value for the validation/improvement of the model.

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