CHARACTERIZING THE SHOCK SENSITIVITY OF HEXANITROSTILBENE BY FLYER IMPACT EXPERIMENTS AND SIMULATIONS

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The shock sensitivity and ignition behavior of explosives and propellants are important safety characteristics for developing insensitive munitions (IM) and ignition systems. Material properties related to shock sensitivity are usually examined in initiation experiments such as flyer impact or gap tests resulting in critical velocities or gap lengths. With advanced methods, models for describing and simulating the initiation behavior of explosives are derived from these experiments but the universality of these models, e.g. I&G and HVRB, is questionable. Generally, these must be tuned for each experiment and depend on the experimental results, from which they are generated. Pop-plots from extensive experiments are usually the basis for optimizing these ignition models used in hydro codes.

In this work different initiation models are evaluated for the applicability to predict the results of flyer impact experiments, using different hydro codes. Therefore, initiation models and parameters for HNS available in literature are used in flyer impact simulations and the results are compared and assessed based on the critical flyer velocity with respect to initiation. For deriving future initiation models an experimental setup for the generation of Pop-plots is introduced which could reduce the experimental effort in the future. This setup utilizes the miniaturized velocity of detonation measurement method, formally developed at Fraunhofer ICT.

1 Introduction

Sensitivity testing and characterization of ignition performance are key components in the development and assessment of insensitive munition (IM) and ignition systems. New IM and its components must undergo severe testing taking various hazards into account, e.g. fragment impact and sympathetic reaction [1]. These two experiments examine the shock sensitivity of the final system which usually is not time- and cost-efficient.

Pre-scanning energetic materials of a system using standardized experiments, i.e., flyer impact or gap tests, in combination with numerical simulations reduces experimental effort and enables insight in the processes leading to the initiation of the explosives.

Reactive flow models phenomenologically describe the compression, ignition, growth and build up to a complete reaction based on experimental data regarding the energetic material of interest [2,3]. Parameterization of these models is usually optimized for run-to-detonation distance versus input shock pressure experiments (Pop-plots) or embedded pressure or velocity gauge measurements.

In this work two ignition models with published parameter sets for the here investigated explosive HNS are used in two different hydrocodes for simulating flyer impact experiments. The critical impact velocity for initiation is determined, assessed for consistency. In addition, a new methodology for future generation of Pop-plots, which was originally developed for measuring detonation velocities of very small explosive charges, is being evaluated for the first time [4]. The goal is to be able to reduce the effort for the creation of Pop-plots in the future.

2 Theory

Simulating the shock induced initiation of explosives is usually done by relying on pressure-based models. The Ignition & Growth model (I&G) was introduced by Lee and Tarver in 1980 [5]. Another model is the History Variable Reactive Burn model (HVRB) [6]. Both combine the equation of state (EOS) of the products (index g for gaseous) with the reactants (index s for solid) by the rate parameter λ describing the percentage of reacted explosive.

$$P(\rho, e, \lambda) = (1-\lambda) P_s(\rho, e) + \lambda\, P_g(\rho, e) \text{ with } 0 \leq \lambda \leq 1$$

The models differ in the definition of the rate equation. The I&G defines the rate as

$$\begin{aligned}\frac{\mathrm{d}\lambda}{\mathrm{dt}} = \mathrm{I}(1-\lambda)^{\mathrm{b}}(1/\mathrm{v}-1-\mathrm{a})^{\mathrm{x}}\mathrm{H}\left(\lambda_{\mathrm{ig,max}}-\lambda\right) \\ + \mathrm{G}_1(1-\lambda)^{\mathrm{c}}\lambda^{\mathrm{d}}\mathrm{P}^{\mathrm{y}}\mathrm{H}\left(\lambda_{\mathrm{G}_1,\mathrm{max}}-\lambda\right) \\ + \mathrm{G}_2(1-\lambda)^{\mathrm{e}}\lambda^{\mathrm{g}}\mathrm{P}^{\mathrm{z}}\mathrm{H}\left(\lambda-\lambda_{\mathrm{G}_2,\mathrm{min}}\right)\end{aligned}$$

with the Heaviside distribution H and I, G_1, G_2, a, b, c, d, e, g, x, y and z are modelling parameters. The HVRB models the rate and rate parameter by

$$\phi(t) = \frac{1}{\tau_R}\int_0^t \left(\frac{\max(0, P - P_I)}{P_R}\right)^Z d\tau$$

$$\lambda = 1 - \left(1 - \min\left(1, \frac{\phi^M}{X}\right)\right)^X$$

with $\tau_R = 1\,\mu s$ and the parameters P_R, P_I, Z, M and X. Both the I&G and the HVRB are fitted to and tuned with experimental data and therefore are sensitive to changes in the experimental setup.

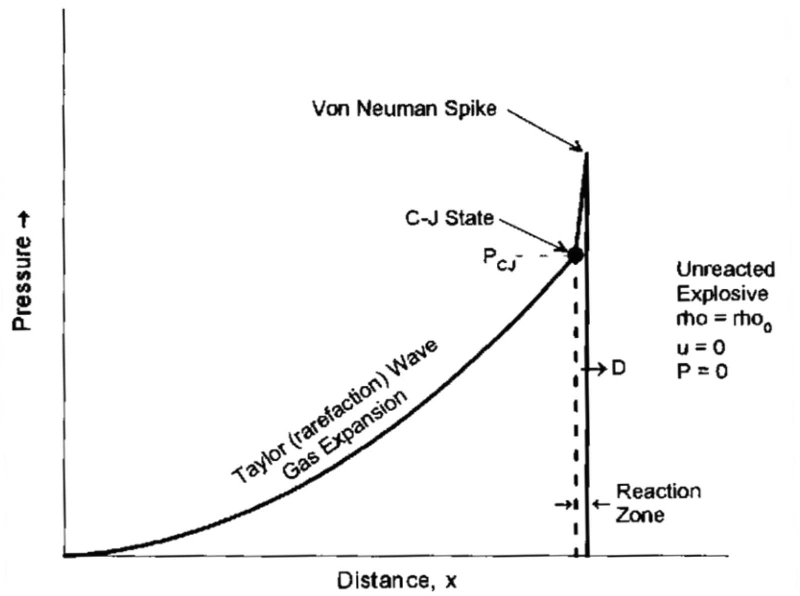

Figure 1: Exemplary detonation front (taken from [2]).

Commonly used experiments for this purpose are run distance to detonation measurements resulting in Pop-plots. They describe the relation between the initial pressure or particle velocity behind the shock transmitted into the explosive and the distance in the energetic material needed to build up to a full-scale detonation [7,8].
The shock travelling into the booster starts a reaction of the explosive. If the reaction is self-sustaining (more energy released than dissipated) a detonation front is formed. A detonation wave generates an instant rise of pressure with a Von-Neumann-Spike,

the reaction zone leading to the Chapman-Jouguet-Point where equilibrium occurs and the following Taylor wave (c.f. Figure 1).

3 Simulation Setup and Analysis

Numerical simulations are conducted with the commercial hydrocodes LS-DYNA [9] and SPEED [10]. A flyer impact experiment consisting of a 3 mm thick copper flyer with a diameter of 18 mm impacting on an HNS booster with a diameter of 21 mm and a height of 19 mm is modelled. Since the experiment is rotationally symmetrical the simulation models can be reduced to two dimensions. In SPEED the 2D Multi-Material Solver (Euler) is used with a global cell size of 50x50 µm². Figure 2 shows the simulation model in SPEED with gauge points on the y-axis and on the edge of the booster. The copper flyer (left) travels at various velocities impacting the HNS booster (right).

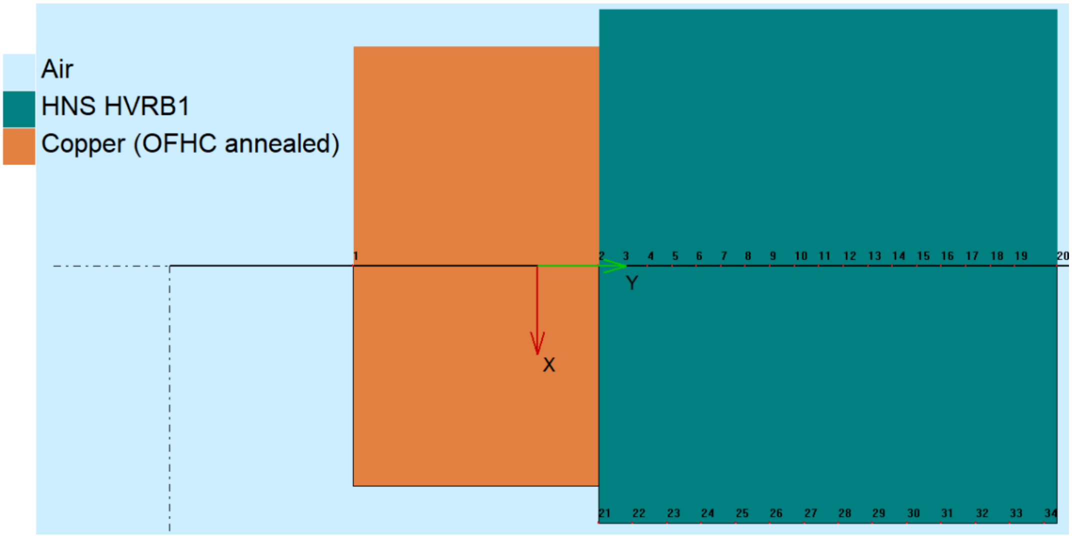

Figure 2: 2D Simulation model in SPEED with axial and surface gauge points. The copper flyer (left) impacts the HNS booster (right) at various velocities.

A second case was build in LS-DYNA using two different 2D approaches, a pure lagrangian simulation and a pure sALE simulation. In both the lagrangian simulation and sALE, the flyer was defined identically by MAT_STEINBERG and an EOS_GRUNEISEN both with the parameters given in Table 1. The HNS-target was defined by a MAT_NULL model, that solely requires the density and the EOS_IGNITION_AND_GROWTH_OF_REACTION_IN_HE with the parameters given in

Table 2. For both cases, the spacial resolution was defined by a grid size of 0.1 mm. For the lagrangian case, a SECTION_SHELL was defined by ELFORM=14 for an axisymmetric model with NIP=4 (fully integrated). The velocity was applied by INITIAL_VELOCITY_GENERATION. For the lagrangian interaction with the target, a CONTACT_2D_AUTOMATIC_SINGLE_SURFACE was applied.

Accordingly for the sALE the equivalent key word is STRUCTURED_MULTI-MATERIAL_GROUP_AXISYM. The 2D sALE domain was filled with MAT_VACUUM and the flyer/target using the PART keywords from the lagrangian simulation within the keyword STRUCTURED_MESH_VOLUME_FILLING, which also allows to define an initial velocity for the flyer. In both cases, the pressure and particle velocity were recorded along the axis using a HISTORY_SHELL_SET (lagrangian) and DATABASE_TRACER (sALE). Both cases were validated for the impact pressure (while turning the reaction model off) that is representative for a specific velocity, by comparing the results to the analytical solution.

The material parameters for the SPEED and LS-DYNA models are summarised in Table 1. LS-DYNA does not support the use of HVRB, so only the I&G model is simulated. Both the I&G and the HVRB parameters are shown in
Table 2.

Table 1: Material parameters for simulation in SPEED and LS-DYNA [11]

Material	Density	Parameters
HNS	ρ = 1.6 g/cm³	Shock Hugoniot: C0 = 1450 m/s S0 = 2.37 JWL: A = 5.3625E+11 Pa B = 2.702E+10 Pa R_1 = 5.4 R_2 = 1.8 ω = 0.45 e-JWL = 7E+06 J/kg c_v = 625 J/kg/K
Copper	ρ = 8.93 g/cm³	Shock Hugoniot: C0 = 3940 m/s S0 = 1.489

Table 2: Initiation Models for HNS

Model	Density	Parameters
I&G [11]	ρ = 1.6 g/cm³	I = 1.4E+12 1/s b = c = d = e = g 0.667 a = 0.26691 x = 4 F_{igmax} = 0.08 G_1 = 3.7E+09 1/s y = 2 F_{g1max} = 1 G_2 = 1.48E+10 1/s z = 3 F_{g2min} = 0
HVRB [12]	ρ = 1.6 g/cm³	P_I = 5E+08 Pa P_R = 4.25E+09 Pa Z = 3.55 M = 1.5 X = 1

The analysis is based on the time pressure curves of the axial gauge points. By using impedance matching the impact pressure is calculated and compared to the simulated value. Varying the impact velocity gives different impact pressures between the copper flyer and the HNS.

If a full-scale detonation wave is detected in the data, the initial axis gauge point position at which it occurs is the run-to-detonation distance for the calculated impact pressure. This evaluated run distance to detonation is then plotted over the impact pressure.

4 Results

By lowering the impact velocity, the transmitted shock pressure is changed until no more steady detonation occurs. These critical velocities and the corresponding pressures calculated by impedance matching are summarized in Table 4. Both LS-DYNA simulation models are consistent and result in the same critical velocity v_{crit}.

Table 4: Critical velocities and impact pressures for initiation models.

Model	v_{crit} in m/s	impact pressure in GPa
I&G	635	2.52
HVRB	620	2.44
LS-DYNA I&G (both models)	300	0.92

Since both the I&G and HVRB simulations in SPEED deliver similar results, the Pop-plot study is only done with one model, the HVRB. Therefore, the copper flyer impact is simulated at 650, 700, 750 and 800 m/s, the impact pressure is calculated and the run distance to detonation is evaluated for the four velocities and the critical value of

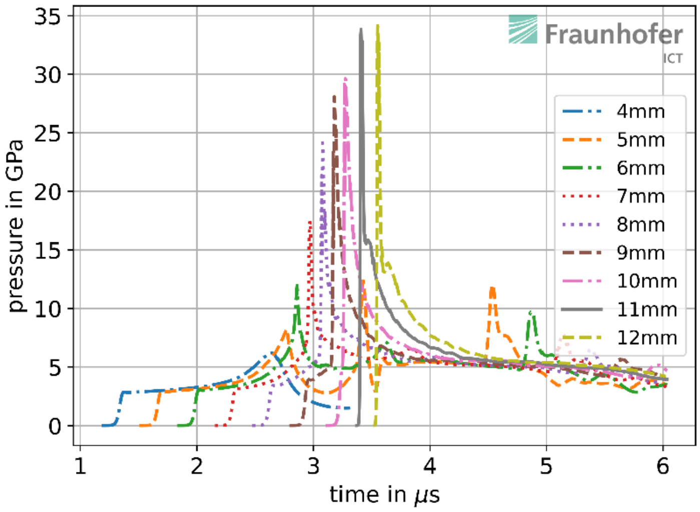

Figure 3: Pressure curves for v_{crit} = 620 m/s. At 11 mm full detonation occurs.

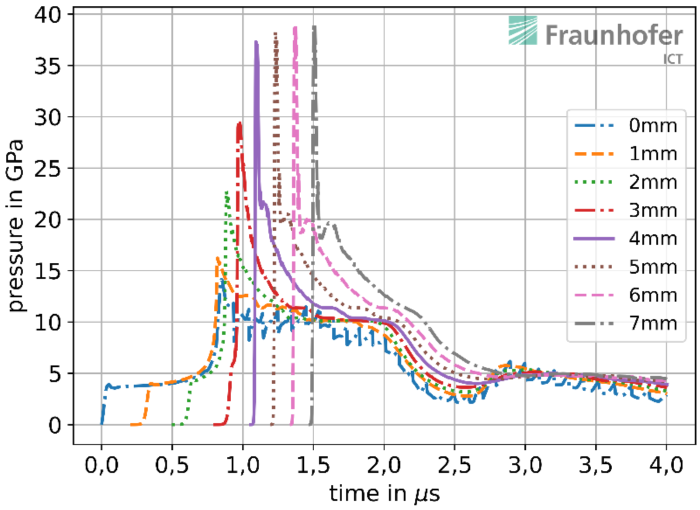

Figure 4: Pressure curves for 800 m/s. At 4 mm full detonation occurs.

620 m/s as well. In Figure 3 and Figure 4 the solid lines show the pressure curves of the gauge point at which a full detonation occurs for 620 and 800 m/s impact velocity. Plotting the initial position of the corresponding gauge points over the impact pressures for all velocities gives the Pop-plot for HNS in Figure 5.

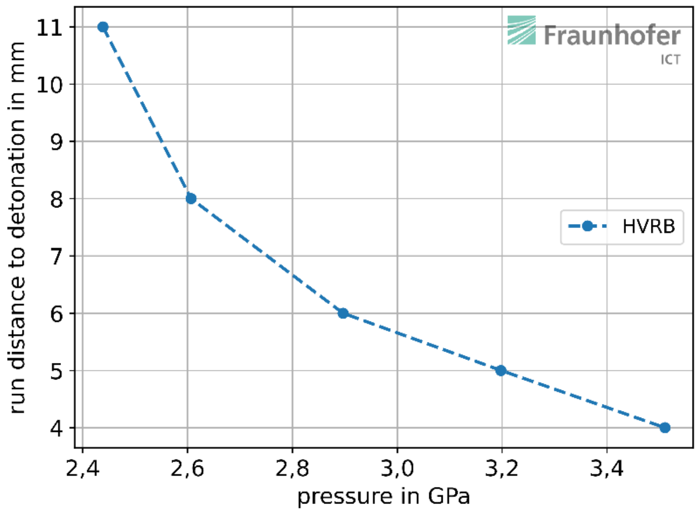

Figure 5: Pop-plot for HNS from HVRB simulations.

The simulations were complemented by impact tests with identical geometric dimensions of the flyer and HNS using a 20 mm munition test device. However, limited by the ballistic stability of the projectile, the velocity was limited to 850 m/s, so that a direct comparison with the simulated initiation threshold was not possible. Nevertheless, the opportunity existed to test the scaled down detonation velocity measurement methodology, formally developed at Fraunhofer ICT [4] for the first time in terms of its suitability for generating Pop-plots. The VoD-probe consists of a flexible printed ciruit board that provides 16 short circuit pins in a distance of 1.4 mm. By applying the VoD-probe on the surface of the explosive sample, a potentially axially initiated and highly curved detonation front reaches the cylindrical surface of the sample with an according time delay, which must be considered for the interpretation of the signals. The challenge here is to interpret the timing of the signals and back-calculate it to define a position of initiation.

Figure 6 shows first measurement results with this setup, using 13 channels with an equivalent measurement length of 20 mm. In this case, the temporal occurance of the short circuit signals was in the according spacial order for an impact at 850 m/s.

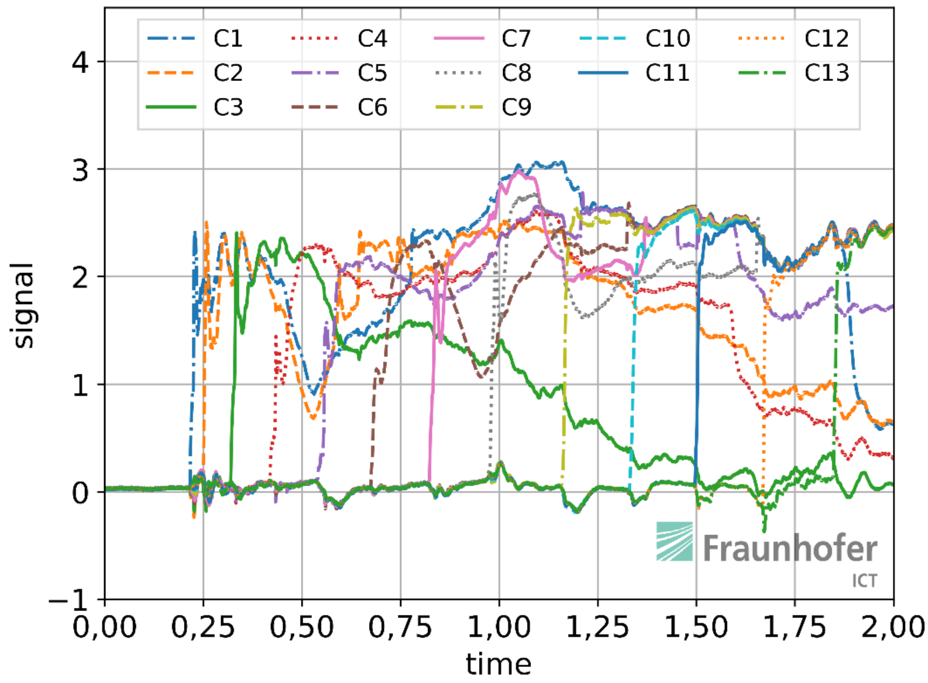

Figure 6: VoD measurement for flyer impact

This suggests that initiation was relatively planar and not limited to a core area on the axis. The first three pins on the first 4 mm occur at shorter time intervals than the following stationary detonation. This indicates that the detonation front formed within this distance, which is consistent with the simulation results in Figure 4. However, further measurements, especially in the initiation threshold region, are needed for a general statement about the possibility of creating Pop-plots with this method.

5 Conclusion and Outlook

By simulating flyer experiments with initiation models the initiation behavior of explosives is described for long shock pulses. While I&G and HVRB modelling in SPEED deliver reasonable and similar results, the low initiation pressure in LS-DYNA, which is not consistent to the SPEED values, is part of further investigations. The ability to create Pop-plots with the new setup shows promising results, but further work is needed here for a final evaluation of the capabilities.

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