



Calibration of Impact Ignition from Shear-Band Formation on The Mesoscale

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ABSTRACT

Relying on test results in [1], we proposed in [2] a macroscopic impact ignition model for low velocity impact situations, in terms of the product PD (P =pressure, D =plastic deformation rate). Here we upgrade this model by taking into account the time duration to ignition for different PD levels. Our macroscopic impact ignition model is now based on, and calibrated from, 1D simulations of pure torsion on the mesoscale. We assume that low velocity impact ignition is invoked by shear localization and formation of shear bands. We denote by $(PD)_L$ the macroscopic shear localization threshold. When $PD > (PD)_L$ in a macroscopic cell, shear bands start to form there. The shear bands then develop and heat up towards the ignition temperature. We further assume that the time duration from localization to ignition $h = t_{ig} - t_L$ is also dependent on PD . Using 1D simulations of shear band formation in torsion similar to [3], we calibrate $(PD)_L$ and $h(PD)$, which we can then use in macroscopic hydrocode simulations. Our mesoscale simulations depend on a realistic strength model for explosives. This model employs the overstress approach to dynamic viscoplasticity [4], and its main feature here is the pressure dependence of its plastic flow curve.

INTRODUCTION

Boyle Frey and Blake [1] performed dynamic tests in which they loaded various explosive samples to characterize their low velocity impact ignition threshold. Under high velocity impact, explosives would mainly ignite by a pore collapse mechanism, but below some impact velocity threshold, ignition would come about by a shear-band formation mechanism. In their low velocity impact tests, Boyle and coauthors were able to change separately pressure and impact velocity (which can be translated into strain rate). They found that the macroscopic ignition threshold can be expressed in terms of the product of pressure and strain rate (PD), where P is pressure and D is strain rate (essentially plastic strain rate). We may deduce from those tests that low velocity impact occurs when PD is above a threshold value $(PD)_{th}$. Assuming that this is an appropriate ignition criterion, we evaluated in [2] the impact ignition threshold of an HMX based explosive from Steven-test data [5].

Here we try to understand and calibrate low velocity impact ignition from simulations on the mesoscale. As in [3], we're able to perform 1D simulations with shear band formation for torsion of thin-walled tubes. From such simulations with explosives, we learn that low velocity impact ignition is related to shear localization and shear band formation. Such an ignition is a two-stage process: 1) shear localization of the plastic flow; and 2) formation of shear bands and their heating up to the explosive ignition temperature.

In what follows we describe our 1D mesoscopic simulations and show how to extract from them: 1) the macroscopic localization threshold $(PD)_L$ (which replaces $(PD)_{th}$ of our previous form of the model [2]; and 2) the time duration h from localization to ignition.

TORSION OF A THIN-WALLED TUBE ON THE MESOSCALE

Recently we developed a 1D model for torsion of thin-walled tubes to predict the formation of adiabatic shear bands on the mesoscale. We run these simulations with a mesh of $1\mu m$, and the length of the tube is 2 to 5mm. We used this model for metal tubes, and compared the results to tests on various types of steel [6]. The set of equations that we solve with this model includes: 1) momentum equation; 2) strain rate equation; 3) plastic strain rate equation; 4) hardening and softening equation; 5) heat balance equation. These five equations are outlined in references [3] and [7]. We use there the overstress approach to dynamic viscoplasticity [4], with which we specify: 1) the quasistatic yield stress; 2) a flow curve which gives the effective plastic deformation rate as function of the overstress; and 3) a failure strain. Comparing runs with the overstress approach to runs with the traditional flowstress approach (where the flowstress is specified, and the stress state is determined by what is known as radial return), we conclude that the overstress approach is superior here in terms of stability and accuracy. We further discuss this issue in [7].

To solve the system of equations described above we: 1) define as unknowns the values of the five unknown functions mentioned above at the mesh points; and 2) express the space derivatives of those functions by finite difference approximations. We obtain a system of $5n$ (n =number of cells in the tube) simultaneous rate equations (which are ODEs), which we solve with a standard ODE solver with the appropriate boundary conditions. We load the tube in torsion by applying equal, but opposite in sense, tangential velocities at the tube ends.

To create shear localization in the plastic shear flow we need to specify a perturbation. We specify the perturbation at the tube mid length, and the shear band develops there. There are several possible ways to specify a perturbation. We choose to specify the perturbation as a 1% reduction of the initial yield stress at the two cells next to the tube mid plane.

To save space we don't outline here the flow equations, and those can be found in [3] and [7]. What is different here from our previous work is that the tube material is an explosive, and as is well known the mechanical response of polymer bonded explosives, and of polymers in general, is much different from that of metals. As mentioned above, we use the overstress approach to dynamic viscoplasticity. By this approach we define 1) a quasistatic yield stress τ_{qs} ; 2) a flow curve which defines the effective plastic strain rate in shear as function of the equivalent stress in shear; and 3) a failure strain in shear. The main issue here is that τ_{qs} may depend on the pressure P :

$$\tau_{qs} = \tau_0 F_p F_T F_f$$

$$F_p = 1 + A_p P \quad F_T = (T_m - T / T_m - T_0)^\alpha \quad F_f = \exp\left(-\frac{t - t_f}{t_{ref}}\right) \quad (1)$$

where t_f =time when a certain cell reaches the strain to failure, t_{ref} =a reference time which determines the rate of strength loss beyond the strain to failure, T_m =melting temperature, and where the strain to failure is given by:

$$\gamma_f = \gamma_{f0} (1 + A_f P) \quad (2)$$

For the flow curve we assume a linear relation:

$$\begin{aligned} \dot{\gamma}_{eff}^p &= A_\gamma (\tau_{eq} - \tau_{qs}) \\ \tau_{eq} &= |\tau| \end{aligned} \quad (3)$$

Next, we show results of a typical run of the simulation code, where the end tangential velocities are 15 and -15m/s, and the average (macroscopic) strain rate is therefore $D=15e-3/\mu s=15,000/s$. Pressure is not part of this pure shear flow. We therefore specify it from the outset, and in this typical run we use $P=0.5GPa$, so that $PD=7.5e-3GPa/\mu s$. The values of the parameters that we use in such a run are: $T_m=500K$, $\alpha=1.1$, G (shear modulus) $=2.5GPa$, C_V (heat capacity) $=1e-3kJ/g$, k (heat conductivity) $=5e-10GPa*mm^2/\mu s/K$, $\tau_0=0.1GPa$, $\gamma_{f0}=0.05$, $t_{ref}=100\mu s$, $A_\gamma=1.0/GPa/\mu s$, $A_f=1./GPa$. We show two types of figures: 1) temperature profiles along the tube every $50\mu s$ (Fig. 1); and 2) temperature history in the developing shear band (Fig. 2). We see from Figs. 1 and 2 that: 1) for the parameters used, the calculation is beyond the localization threshold; and 2) after about $50\mu s$, the temperature in the shear band is above the ignition temperature of this explosive (570K).

It's not difficult to see that the slope of the flow curve A_γ controls what is known with the flowstress approach as strain rate sensitivity. Lower values of A_γ push the stress needed for full plastic flow and for a given strain rate to higher values. We see this in Fig. 3, where the value of A_γ is lowered to $0.3/GPa/\mu s$, and all other parameters stay the same. We see from Fig. 3 that for this value of A_γ the shear flow in the tube is just at the localization threshold, and that beyond about $150\mu s$, the excess temperature at the perturbation location hardly changes.

Next, we check how shear velocity and pressure influence the localization process. We find that shear velocity has little influence, and that pressure has a strong influence. It seems that pressure influence comes about through its effect on the quasistatic yield stress. Although shear velocity has little influence, we still adhere to the experimental findings of [1], that localization threshold depends on the product PD , as stated above. Changing the shear velocity, we have to change the pressure accordingly to stay at PD_L . But changing the pressure would take the perturbation out of the localization threshold, unless we change the slope A_γ accordingly.

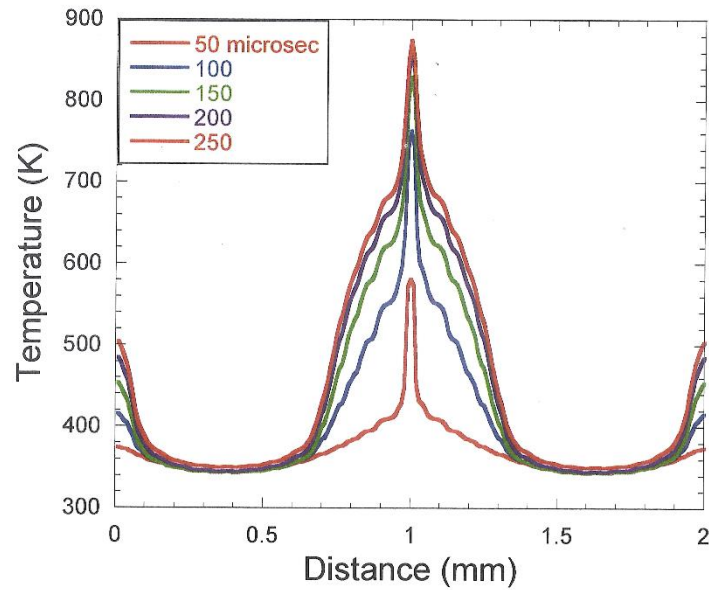


Figure 1. A typical run with $A_\gamma=1.0/\text{GPa}/\mu\text{s}$. Temperature profiles along the tube every 50 μs .

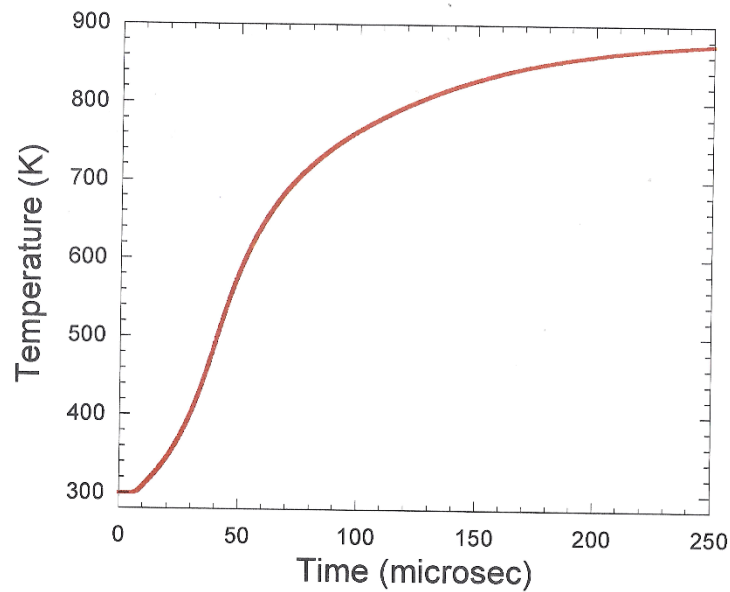


Figure 2. Maximum temperature history at the shear band shown in Fig. 1.

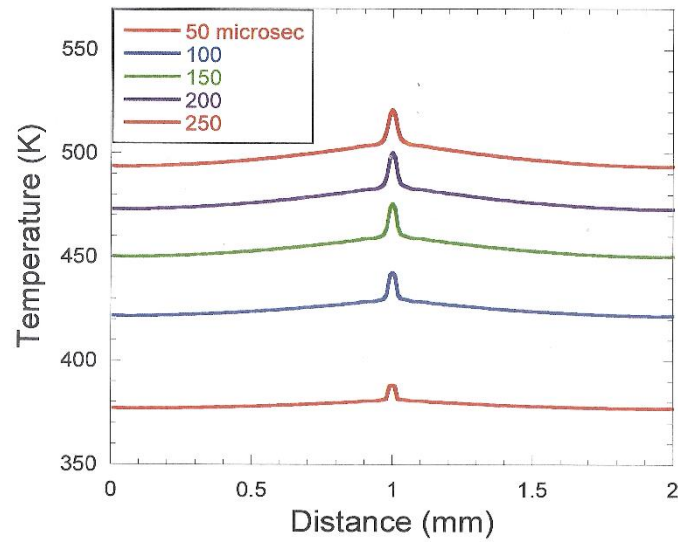


Figure 3. Same as Fig. 1, but with $A_\gamma=0.3/\text{GPa}/\mu\text{s}$.

In Fig. 4 we show the values of A_γ that keep the perturbation at the localization threshold for $\text{PD}=15\text{e-}3/\mu\text{s}$ and for different values of the shear velocity.

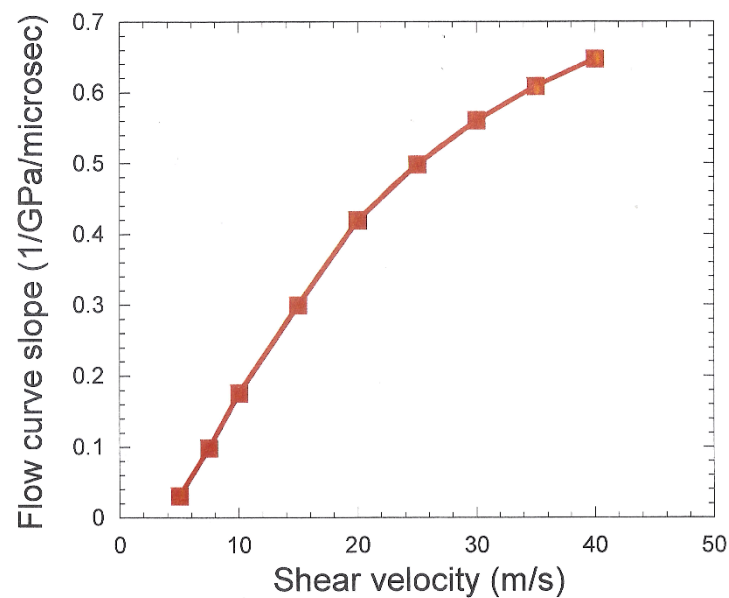


Figure 4. Flow curve slope as function of the shear velocity needed for the perturbation to stay at the localization threshold, for $\text{PD}_L=15\text{e-}3/\mu\text{s}$.

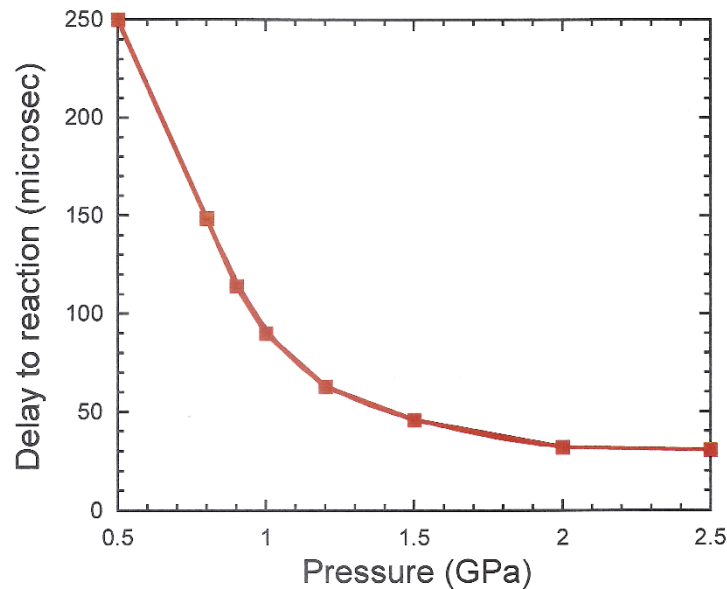


Figure 5. Heat up time (delay) from localization to ignition, for

$PD_L = 15e-3 \text{ GPa}/\mu\text{s}$.

The main purpose of our mesoscale simulation is to predict the heat up time from localization of a shear band to its ignition. In macroscale simulations of low velocity impact, we call it a delay time. In Fig. 5 we show results of heat up times from simulations with a shear velocity of plus and minus 15m/s as before, and pressure values from 0.5 to 2.5 GPa. For $P=0.5\text{GPa}$, the perturbation is at the localization threshold, and the heat up time ($250\mu\text{s}$) is the time needed for the whole tube to heat up to 570K (we ignore here cooling of the tube from the radial boundaries). We see from Fig. 5 that for increasing values of $P>0.5\text{GPa}$, the heat up time decreases down to $30\mu\text{s}$.

SUMMARY

We perform 1D simulations of torsion of a thin-walled tube of an HMX based explosive on the mesoscale. The simulations are on the mesoscale, because we follow the localization and development of a shear band at the tube middle section. We trigger the shear localization by planting there a small perturbation, thereby reducing somewhat the initial yield stress.

We show that there is a localization threshold beyond which a shear band develops from the perturbation. We denote this threshold by PD_L , which is the product of pressure (applied from outside the computation) and the average (macroscopic) strain rate. When $PD>PD_L$, shear localization develops into a shear band and heats up. From the simulation we can calibrate the heat-up time to reach the explosive ignition temperature. This heat-up time would be an input quantity for macroscale low velocity impact simulations.

References

1. V. Boyle, R. Frey and O. Blake, Combined pressure-shear ignition of explosives, 9th Det. Symp. 3-17 (1989).
2. Y. Partom, a threshold criterion for impact ignition, 12th Det. Symp. 831-834 (2002).

3. Y. Partom, Modeling of shear band interaction in 1D torsion, SCCM, AIP conf. proc. 1793 (2015).
4. Y. Partom, Overstress and flowstress approaches to dynamic viscoplasticity, EPJ web conferences 94, 04003 (2015).
5. S.K. Chidester, C.M. Tarver and R.G. Garza, Low amplitude impact testing and analysis of pristine and aged solid explosives, 11th Det. Symp., 93-99 (1998).
6. A. Marchand and J. Duffy, An experimental study of the formation process of adiabatic shear bands in a structural steel, J. Mech. Phys. Solids 36, 251-283 (1987).
7. E. Hanina, Y. Partom, D. Havazelet and O. Sadot, Study of onset of thermoplastic instability by modeling shear band formation in torsion of a thin-walled steel tube, J. Impact Eng. (2017).