

Shock initiation thresholds for projectiles with curved surfaces

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Abstract. The impacts of flat-nosed rods into bare conventional high explosives tend to produce either detonations or very little discernable reaction. In contrast impacts from projectiles with curved striking surfaces, such as round-nosed rods, can produce a range of reactions, some very vigorous, as well as detonations. The current work attempts to explain this complex behaviour. The identification of a predictive threshold as corresponding to the boundary of sub-detonic reactions for low pressure impacts, rather than the boundary between no reaction and detonation, is discussed in the light of experimental results. The structure of the impact shock is explored and the existence of two sonic boundaries is explained. The linkage between the theoretical initiation threshold and one of these sonic boundaries is obtained and the implications of this threshold in terms of the proportion of the diameter of the projectile needed to cause initiation are discussed and the results illustrated using CREST, a hydrocode-based reactive-burn explosive model.

1. Introduction

Historically three series of experiments have been carried out in which spheres or hemispherical round-nosed rods have been fired at bare charges of conventional high explosives (HE) and the degree of reaction carefully measured. Several independent assessments were made as to the HE response produced by each impact, and as a comparison, flat-nosed rods were also used in one of the experimental series.

The first series demonstrates the differences in HE response between flat-nosed rods and spheres [1]. In contrast to flat-nosed rods the spheres had an additional regime between a mild response and detonation in which a vigorous reaction (labelled a sub-detonic reaction) was observed. The second series explored any possible links between the shock sensitivity of the HE and the size of the sub-detonic reaction regime [1]. The third series explored the link between this reaction regime and the size of the impacting projectile [2].

An empirical shock initiation criterion (the so-called James Criterion [3]) and the CREST reactive-burn model [4] will be used to explore the locations of the flat- and round-nosed projectile thresholds; demonstrate the structure of the shock that corresponds to the threshold, and validate an important prediction that arises as a consequence of the HE response to curved projectiles.

2. Projectile impact experiments

The first series of experiments consisted of steel flat-nosed rods and spheres impacting bare cylinders of melt cast Composition B. The projectile diameter was kept constant throughout at 13.15 mm for the rod and 12.9 mm for the sphere. The degree of reaction was obtained from blast overpressures



normalized to overpressures from charges detonated using high-voltage bridgewire detonators. The reaction was also independently assessed from high speed film and video recordings, damage to the surroundings and the amount of HE recovered. For the flat-nosed rod impacts only one result from 32 firings was identified as lying between non-reaction and detonation.

Figure 1 shows the frequency and position (in terms of velocity) of the detonation, sub-detononic and no-response events recorded for steel sphere impacts into the same explosive composition.

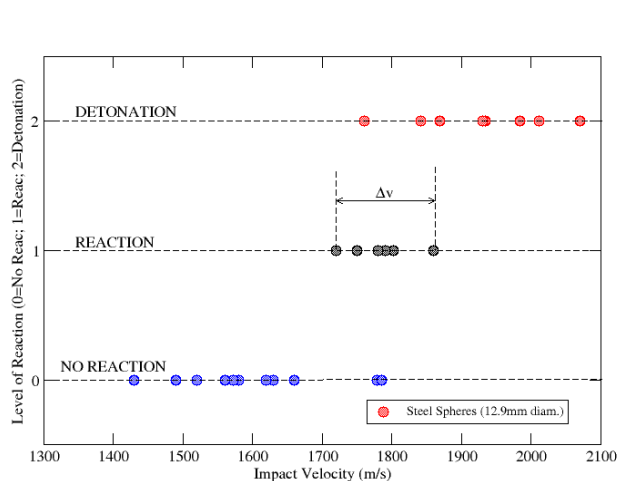


Figure 1. Sphere impacts into cast Composition B, density 1.66 g/cc.

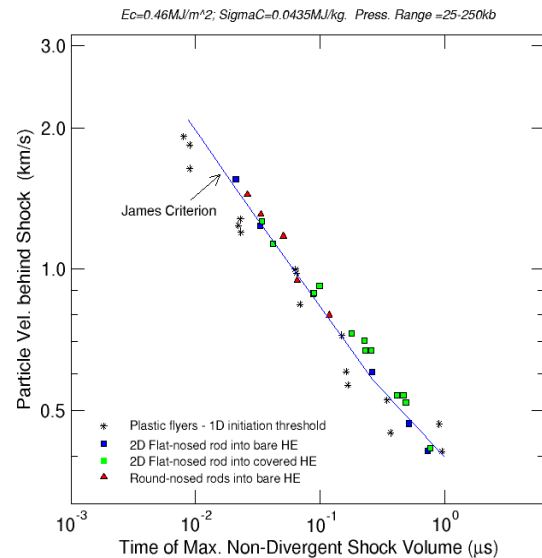


Figure 2. The common threshold produced by the time terms for flyers, flat and round-nosed rods impacting PBX9404.

It can be seen from figure 1 that there is some overlap between the three regimes. This may be due to a number of factors including errors in measuring the velocity, and shock sensitivity effects due to HE density variations. However, the sub-detononic reaction regime can be seen to be relatively extensive in terms of the range of impact velocities over which it occurs ($\Delta v = 140$ m/s).

In the second experimental series a 15 mm diameter steel ball was fired into a variety of explosives, ranging from PETN to RDX-based formulations, in order to obtain the onset of both reaction and detonation, hence obtaining the extent of Δv . Small scale gap tests were also carried out on these explosives in order to gauge their relative shock sensitivity. The results indicate a weak correlation between shock sensitivity and Δv [1].

The third set of experiments concentrated on two explosives and two sphere diameters [2]. The results are summarised in table 1. Here there is a strong correlation between sphere size and Δv . The largest spheres, which have the lowest impact pressure and hence the longest run to detonation, have the greatest value of Δv .

3. Empirical initiation criterion

Criteria that allow a common threshold for different projectile geometries impacting the same explosive require the calculation of some measure of the energy within the shocked HE and a time term coupled to the projectile geometry. The James Criterion [3] has a threshold defined by

$$1 = \frac{E_c}{P_{ut}} + \frac{\Sigma_c}{\frac{1}{2}u^2}, \quad (1)$$

where E_c and Σ_c are shock sensitivity coefficients which are constant for a given explosive and are found from experiments; P and u are the pressure and particle velocity behind the non-divergent

region of the shock in the HE (found from projectile impact velocities by impedance mismatch techniques [1]) and τ is a time term relating to the projectile geometry. For initiation to occur the right hand side of the equation must be equal to or less than unity. The time term is defined as the time at which the maximum volume of non-divergent shock is present in the HE during an impact which corresponds to the initiation threshold. It equates to $2s/W_F$ for 1D flyers (s is the flyer thickness and W_F is the shock velocity in the flyer); and $D/6c$ for flat-nosed rods (D is the rod diameter and c the sound speed in the shocked, but yet-to-react, explosive).

Table 1. Dependence of Δv on sphere size. “ v (det.)” and “ v (reac.)” relate to the impact velocities at the onset of detonation and reaction respectively; D is the sphere diameter.

Explosive	D_0 mm	$v(\text{det})$ m/s	$v(\text{reac})$ m/s	Δv m/s	$E_c(\text{det})$ MJ/m ²	$E_c(\text{reac})$ MJ/m ²
HMX/RDX/TNT /Wax/Terylene 64/4/30/1/1	15.13	1696	1653	43	2.01	1.93
	60.51	1183	823	360	4.33	2.27
HMX/ Polyethylene/ Oleic Acid/ Terylene 95/3.9/0.6/0.5	15.13	1313	1269	44	1.29	1.22
	60.51	882	646	236	2.57	1.47

An inspection of experimental initiation thresholds for high pressure impacts of round-nosed rods into PBX 9404 [5], where no sub-detonic response is recorded, indicates a time term of $D/18c$ is needed to allow these curved projectiles to lie on a common threshold with flyers and flat-nosed rods, as is shown in figure 2, despite the curved-projectile shock having some divergence almost from the time of impact.

Using this time term in conjunction with the four velocities per explosive listed in table 1 shows that approximately a constant value of E_c can be calculated for the velocities at the boundaries of both reaction and detonation (which almost coincide) for the small diameter sphere; and this agrees with the calculated E_c value at the *reaction* boundary for the large sphere. The *detonation* boundary of the large sphere gives a value of E_c that is about double the other values. This observation holds for both explosives. Note that for lack of any other evidence it is assumed that all the impacts have high enough pressures to be able to approximate the effect of the Σ_c term in equation (1) as zero. Consequently the use of the $D/18c$ term gives a constant value of E_c that follows the detonation threshold at relatively high pressures (which result from small-projectile impacts), and the reaction threshold at lower pressures (correlated with impacts of large projectiles).

4. Hydrocode simulation of shock

Figure 3 shows a hydrocode simulation of a hemisphere impacting bare explosive (modelled as inert in this calculation). The contact ring shown in the figure initially has a very high radial phase velocity across the surface of the HE. Initially it is supersonic with respect to all the target material. Eventually the phase velocity drops to become subsonic with respect to the shocked material behind it while still being supersonic with respect to the unshocked HE ahead of it (the first sonic boundary). Later the contact ring becomes subsonic with respect to all the target material (the second sonic boundary) and at this point a jet starts to form between the projectile and the explosive.

Figure 4 shows the simulation time history of pressure measurements made at the contact ring (upper line) and on the centre line of the main shock volume (lower line).

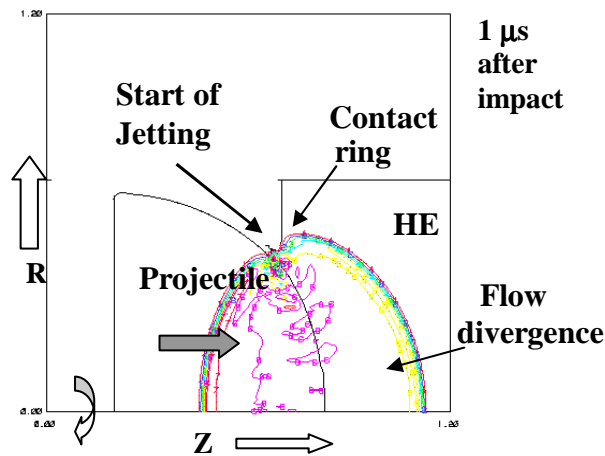


Figure 3. Inert simulation of hemispherical impact at late time showing pressure contours. R and Z axes are 12 mm in extent and the 9 pressure contours are at 0.8 GPa intervals with 7.2 GPa as the maximum.

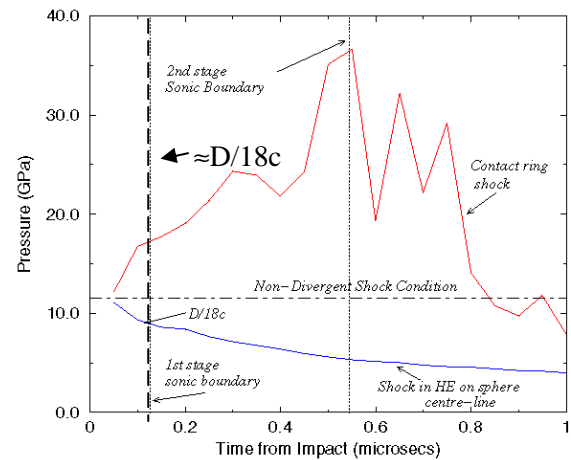


Figure 4. The hydrocode calculation of the evolution of pressure in the contact ring and central shock volume. Note how the divergent central shock differs from a non-divergent condition.

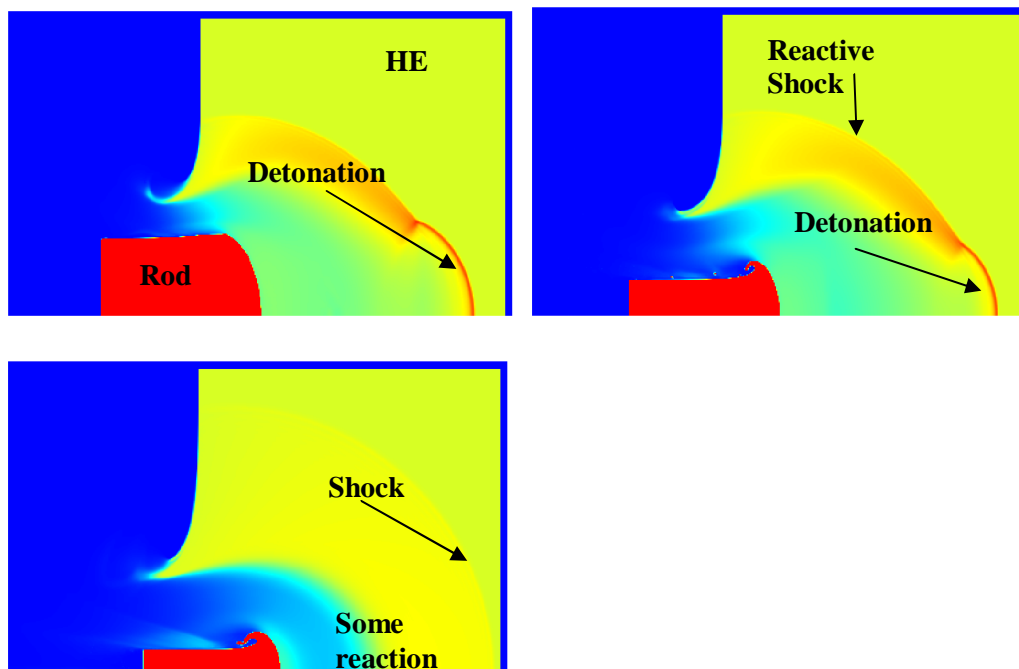


Figure 5. Density contours (green = 1.84 g/cc, orange=2.8 g/cc in the HE) from a CREST reactive burn simulation showing the reactive shock generated in the HE. Top left, detonation is caused by 13.15 mm rod; top right has detonation still generated although the shank diameter of the rod is reduced to 6 mm; bottom is a non-detonation with a 4 mm rod. Rod velocity=1500 m/s in all simulations and the curvature of the rod face is constant.

Although pressure is higher in the contact ring than in the main volume, it is very transient when seen by any given region of the HE. Consequently it is the main shock volume that is considered to be

involved in initiation. By inspection, D/18c is most closely associated with the first sonic boundary. This implies that, unlike a flat-nosed rod, the sphere's entire striking surface is not needed to cause initiation. This is shown in the CREST reactive burn simulation (figure 5) where a hemispherical-nosed rod impacts the HE at a given velocity (1500 m/s), and the curvature of the face is kept constant but the shank diameter of the rod is altered.

5. Conclusions

Unlike flat-nosed projectiles, curved surface impacts into bare HE can produce a reaction which is vigorous but less than full detonation. The empirical criterion examined predicts the reaction threshold for low pressures and the detonation threshold at high pressures for curved projectiles. This threshold corresponds to the detonation threshold for flat-surface impacts, and the same coefficients can be used for both types of projectile for a given HE with the time terms described above. The additional complexity of the curved surface impacts is due to the diverging shock generated in the HE which extends and weakens the reaction growth, especially at low pressures. This can attenuate reaction that would otherwise have grown to detonation, so producing a regime of vigorous HE responses.

The best estimate of when the curved-surface time term occurs during the evolution of the impact shock is at the first sonic boundary. This means that, unlike for flat-nosed rods, only a fraction of the impacting surface is involved in causing initiation and the "excess" surface can be dispensed with while still obtaining the same threshold.

References

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