LOW SPEED IMPACT OF PRISTINE AND AGED SOLID HIGH EXPLOSIVE

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Low speed impact of explosives has received a great deal of attention in recent years since it represents a credible route to violent explosive reaction and the mechanisms of ignition and growth of reaction are poorly understood. The Steven Test developed at LLNL has produced valuable results for a wide range of compositions and a variety of projectile geometries in a standard target configuration. Complementary studies at LANL have made small changes to the target, most notably the inclusion of an annular gap and an increase in the sample thickness. In this work low speed impact experiments are reported which have been performed on confined samples of a pressed HMX based composition in a Steven test type geometry. A wide range of velocities were applied (30 to 350 $m.s^{-1}$) and test design variables were investigated for round and flat nosed projectile impacts on samples from new manufacture and accelerated ageing. In the standard vehicle both projectiles gave ignitions when the projectile caused a pinch with the rear surface of the vehicle. The change in mechanical properties with age resulted in significantly different pinch thresholds. Differences in the explosive mechanical behaviour were observed throughout the velocity range. In addition the effects of radial gaps, end loading and sample thickness have also been examined.

Introduction

Low speed impact has been identified as a credible accident scenario during handling operations, processing and manufacture. The paucity of relevant experimental data and uncertainty over the ignition and growth mechanisms involved needs to be addressed to ensure that all possible outcomes are adequately considered.

The Steven test developed at LLNL [1] and similar work performed at LANL [2] have provided useful information on the relative sensitiveness of a number of compositions in the test geometries. The unambiguous nature of the results provides an indication that competition between different ignition mechanisms has been avoided and that predictive modelling solutions can be applied. However, the differences between the tests and the different results between and within compositions have left unanswered questions about the factors controlling test outcome. Explosive compositions tested in both the LANL and LLNL configurations have given different threshold and violence levels. The UK explosive EDC37 has given markedly higher threshold velocities in the LLNL test than other HMX based explosives (EDC37 consists of 91% HMX, 1% nitrocellulose and 8% K10).

To develop a better understanding of the processes involved in the ignition and growth of reaction in Steven test type impacts we have performed experiments on the explosive EDC37. A variety of geometries have been investigated with the objective of identifying ignition mechanisms and examining the differences between existing tests.

US Test Results

Steven tests were performed by Chidester on samples of EDC37 in the standard LLNL Steven test. Tests using the 1.2 kg round nosed projectile [3] gave a threshold reaction velocity of 104 m.s^{-1}. This was significantly higher than other HMX based explosives which all fell between 30 and 45 m.s^{-1}. Similarly, impacts with the nubbed nosed projectile generally gave reactions below 30 m.s^{-1} but for EDC37 the threshold lay at 90 m.s^{-1}.

At LANL it was found that 12.7 mm thick samples of PBX 9501 gave a threshold reaction velocity of 55±3 m.s^{-1} in mild steel targets which was attributed, by extrapolation from cover plate dent measurements and post test examination, to a pinch between the front cover plate and the rear of the vehicle. Thicker targets, 25.4 mm deep, were tested and gave a higher threshold for reaction, but this did not correlate with the pinch mechanism. Violence measurements for baseline, aged and thick samples were made as a percentage of the blast energy from a full detonation as measured with the ballistic pendulum. The LANL test gave some violent events.

UK Experiments

Configuration 1: Round nosed impact
Tight annular ring

Initial tests have been based on a Steven test-style arrangement. A review of sample size options was performed to optimise the samples that could be obtained from the available charge. The standard test vehicle shown in Figure 1 comprises a 12.6 mm thick, 70 mm diameter explosive disc, surrounded by a 10 mm thick Teflon ring, encased in a target assembly consisting of a thick steel holder with a 2 mm thick mild steel cover plate. The plate was bolted to the body and initial experiments did not include a strong ring. All components were push-fits and no potting or glue was used.

The 1.6 kg hardened steel, cylindrical projectile (Figure 2) is fired from a 50 mm smooth-bore gas gun towards the centre of the target assembly. The projectile has a hemispherical geometry at one end of its body and a flat face at the other. When available overpressure gauges were positioned around the target assembly and the impact was observed using high speed video. A number of assemblies were subjected to radiography both before and after testing so that the level of damage to the explosive could be assessed in situ.

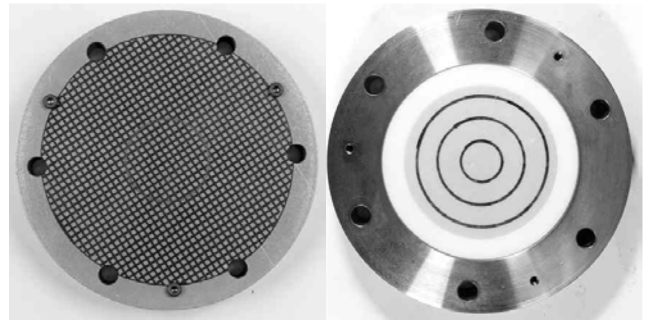

Figure 1 External and internal views of the impact vehicle. A screen printed cover plate was used in early experiments to enhance distortion records.

Figure 2 Test projectile.

In experimental configuration 1 the assembly incorporated a tight fitting annular ring shown above. This was designed to give a close comparison with the Steven test experiments conducted at LLNL. Common features were observed in all impacts in this configuration. At low speed the cover plate was dished and small ripples had formed between the bolts. The explosive had flowed around the nose of the projectile, pushing up the cover plate around the edges of the impact point. Figure 3 illustrates this behaviour for an aged sample impacted at 30 m.s^{-1}.

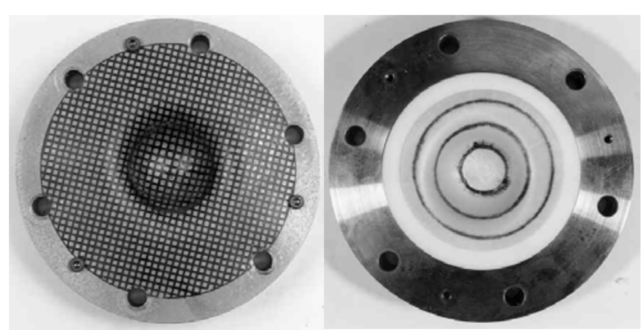

Figure 3 Low speed impact on configuration 1 – no reaction

In this experiment the Parylene coating (included to prevent long term K10 diffusion) had separated from the explosive at the impact point, and minor surface cracking occurred along the top outer edge as the explosive started to flow over the Teflon ring. Examination of the under side of the explosive revealed no signs of damage. The Parylene coating was stripped from the charge and the charge was visually examined. There were no indications of ignition or cracking in the body of the charge.

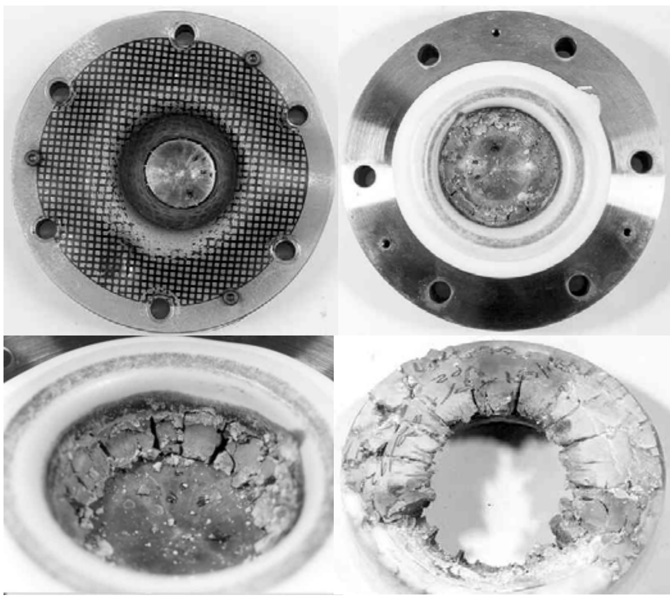

Figure 4 Low speed impact on configuration 1 – reaction

At higher velocities (figure 4) the impact caused pinching between the cover plate and the rear inside face of the test vehicle, perforation of the cover plate and blueing of the metal edges. The explosive flowed away from the point of impact resulting in a large upward distortion of the cover plate around the impact point and ripples between the bolts. It had also flowed radially over the Teflon ring which itself flowed upwards and away from the point of impact allowing some explosive to flow underneath. Large radial cracks had developed in the explosive from the rear face. DYNA2D calculations shown in figure 5 illustrate the flow of an inert material around a round nosed projectile and show many of the features described above.

Post-test examination of the impacted samples indicated that ignition had occurred at pinch. However, comparison of the explosive weights before and after impact indicated that little explosive was consumed in any impact in this geometry even at velocities in excess of 300 $m.s^{-1}$. Where samples were Parylene coated it appeared that ignition had resulted in charring of the coating. In one instance where impact resulted in a gentle pinch and the cover plate was only slightly perforated post-test examination indicated extensive reaction of the Parylene. However, there was no indication that the reaction of the Parylene had communicated to the explosive.

Samples were tested at velocities in excess of 300 $m.s^{-1}$, and whilst the degree of mechanical damage to the vehicle and the explosive progressively increased there was no indication of significant growth of reaction. At the highest velocity more than 99 % of the explosive was recovered after the test.

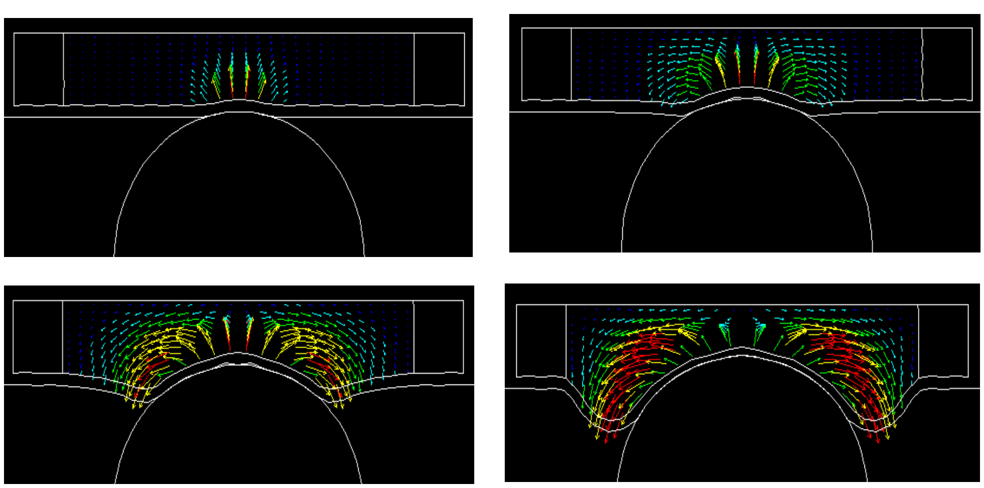

Figure 5 Calculated velocity vectors for a round nosed impact.

Figure 6 An explosive puck retrieved from double thickness impacts.

Fast video evidence indicated that powdered debris was ejected through the ripples in the cover plate during the impact process and material could easily have fallen out of the vehicle during the target disassembly. In no case did the round nosed projectile on this vehicle provoke a measurable reaction from the blast overpressure gauges.

Pinch thresholds were found to be significantly different between aged and unaged samples in the standard geometry. The aged samples gave a pinch threshold between 30 and 44 $m.s^{-1}$, whilst the threshold for unaged material lay in excess of 66 $m.s^{-1}$.

Further weight was lent to the suggestion that ignition occurred at pinch by later experiments using double thickness vehicles which contained two pucks of explosive. The vehicles differed slightly from the standard assembly by the addition of an extra 2 mm thick cover plate and a 5 mm thick strong ring. This increased the containment of the explosive, reduced upwards flow and provided greater confinement around the edges of the cover-plate. All these changes acted to focus more of the energy of the impact into the explosive by restricting its ability to flow away from the projectile. Impacts (120 and 175 $m.s^{-1}$), which caused an indent greater than the thickness of a single puck, failed to provoke ignition and the explosive appeared remarkably undamaged with no evidence of cracks or mechanical failure (figure 6).

At an increased velocity (215 $m.s^{-1}$), predicted to give pinch, a reaction occurred that resulted in rapid cover plate failure and ejection of the explosive. However, a great deal of unreacted explosive could be seen covering the end of the gun and the target stand. Blast overpressure gauge data were not available.

Configuration 2: Round nose impact,
Loose annular confinement

A revised configuration introduced a 2 mm annular gap around the outside of the explosive sample by increasing the internal diameter of the Teflon ring. This was used to determine whether the gap in the LANL configuration contributed to the large differences in response observed in the US results.

Experiments were performed on single thickness samples of unaged explosive at 56 and 122 $m.s^{-1}$. At the lower velocity the cover plate only just formed a pinch with the back face of the vehicle. The cover plate was not perforated. There was evidence of Parylene pyrolysis, and fine radial cracking was evident on the front surface of the sample. The rear of the sample had wider but less numerous radial cracks. Introducing the radial gap had reduced the pinch threshold, and therefore the ignition threshold to below 56 $m.s^{-1}$ from above 66 $m.s^{-1}$.

The explosive in the higher velocity impact had sustained similar damage to the sample impacted at 133 $m.s^{-1}$ in configuration 1 except that the inclusion of the annular gap reduced the damage to the Teflon ring which had been forced upwards and outwards, resulting in gross distortion and several splits in the original configuration.

Configuration 3: Flat nose impact,

In configuration 3 the flat end of the projectile was used. The original vehicle design incorporating a tight fitting annular ring was used in the initial experiments. At impact the projectile cut neat circular discs out of the cover plate and the Parylene coating (if not removed prior to the experiment), and drove them into

Figure 7 Low speed flat nosed projectile impact

the explosive. The explosive appeared to have been compressed under the projectile and to have flowed upwards slightly around the edges of the projectile. The cover plate was rippled around the edges between the bolts. At sub-ignition velocities none of the explosive appeared to have flowed either under or over the top of the Teflon ring.

At low speeds where there was no ignition: the projectile remained stuck in the target as shown in figure 7. On disassembly, it was found that the explosive under projectile had been compressed to a thickness of approximately 1 mm. Measurements of the density and scanning electron microscopy on the compressed material are in progress. There were no signs of ignition, Parylene charring or cracking when the material from inside the vehicle was examined.

At slightly higher velocities, where a pinch could occur between the projectile and the rear inner surface of the vehicle, a small explosive reaction occurred. The cover plate was blown off the vehicle and the explosive was ejected. A distinctive ignition mark was left on the rear inner surface of the vehicle that was mirrored on the cut disc from the cover plate. In tests where blast overpressure gauges were available the output was barely detectable.

Both new and aged samples gave a higher threshold for pinch, and therefore ignition, with a flat nosed projectile than with the round nosed. This is in line with US experience and would be expected from the modelling shown in figure 8. In the calculations with an inert material representing the explosive the initial flow is down and away from the point of impact, as the material becomes fully compressed it tries to flow around the projectile. Experiments were not performed to establish a threshold but it was found to lie between 67 and 90m.s^{-1} for unaged EDC37 and in excess of 75 m.s^{-1} for aged.

Flat nosed projectile impacts were performed on targets containing 2 mm and 5 mm annular gaps between the explosive and the Teflon ring. In each case, the explosive seemed to have flowed under the Teflon ring. Below the pinch/ignition threshold, the material was compressed under the projectile such that a layer of compressed material, about 1 mm thick, extended to the full diameter of the vehicle. The bulk of the explosive was unmarked and uncracked throughout. There was no decrease in the pinch ignition threshold, as had been seen when annular gaps were introduced with the round nosed projectile, and with a 2 mm gap the ignition threshold had increased to over 100 m.s^{-1} for unaged explosive.

Configuration 4: Mechanical loading of the explosive

A final variation in the test geometry was produced by raising the base of the vehicle so that the explosive was subjected to a mechanical loading when the cover plate was bolted down. The mechanical loading did not result in visible damage to the charge. In this geometry flat faced impacts gave explosive reactions at 85 and 52 m.s^{-1} (overpressure gauges were not available but large quantities of ejected, unreacted explosive were observed). There were no black ignition marks on the cut discs or test vehicle inner face.

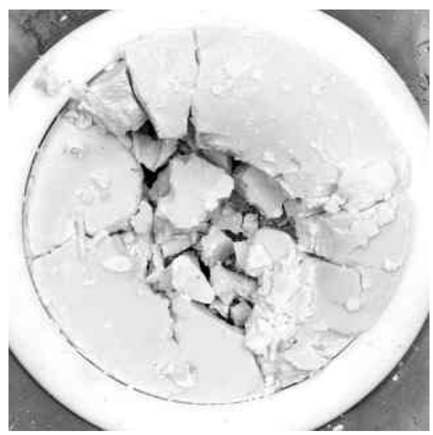

Figure 9 Low speed impact on to a mechanically loaded sample

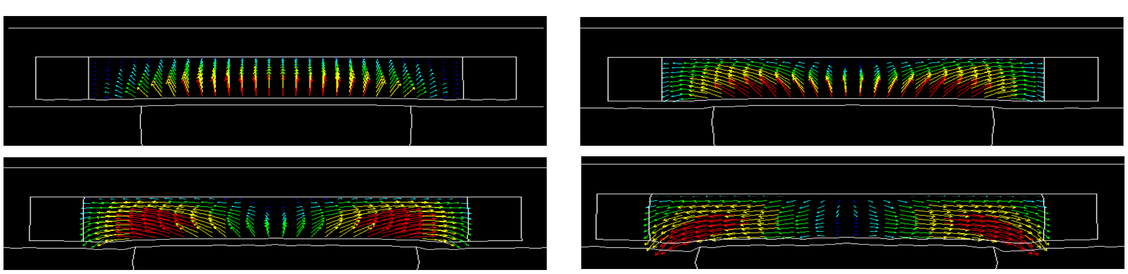

Figure 8 Calculated velocity vectors for a flat nosed impact.

The impact velocity was decreased until explosive was not ejected. At 39 $m.s^{-1}$ (figure 9) a disc was only partially punched from the cover plate. Disassembly of the vehicle indicated that the explosive had behaved quite differently to that observed previously. Under the cover plate, the explosive appeared to have shattered with a region of severe damage and rubblisation under the point of impact and deep radial cracks running to the circumference. There was no indication that the explosive had flowed but the Teflon had started to flow up and away from the point of impact.

Similar experiments using round nosed projectiles also gave higher levels of damage to the explosive and the vehicle when compared to similar velocities applied to experiments on explosives without mechanical loading.

Discussion

Experiments with round nosed projectiles have shown EDC37 to be extremely mobile under low speed impact conditions. Post test analysis revealed that the explosive had flowed away from the point of impact without any visible signs of mechanical failure unless there was a pinch between the front and rear surfaces of the vehicle. EDC37 is a highly loaded HMX based explosive but is relatively weak due to the nitrocellulose/K10 gel binder system. Extensive ageing studies have been performed which have shown no change in the sensitiveness of the explosive in standard powder and small scale charge hazard tests. Quasi-static mechanical properties tests (10^{-4} s^{-1}) have been performed on samples of new manufacture and aged material which showed decreases in the mechanical strength but did not show any change in the hardness of the material, by modulus [4]. However, in this low speed impact regime a marked difference was found between the samples as the aged material had a threshold for pinch that was significantly lower. Chemical analysis has indicated that the proportion of the ingredients in the aged material was consistent with the original manufacture and the major change would appear to be a decrease in the average molecular weight of the nitrocellulose component [5]. Whilst there is no direct evidence for a change in the viscosity of EDC37 with age, GPC measurements have shown a decrease in the intrinsic viscosity of nitrocellulose/THF solutions with the age of the nitrocellulose [6].

In round nosed impacts the flow away from the impactor resulted in only small volumes of explosive becoming involved in the pinch and lower pressures in the material away from the point of pinch. Post test examination of the explosive samples where pinch had occurred revealed large radial cracks originating from the rear surface. There was no evidence from visual examination of the internal crack surfaces of flame front propagation or incipient reaction. Even at the highest velocities there was no evidence of reaction propagation or violent responses.

US experiments at LLNL on EDC37 have indicated that, in the geometry of the US test, EDC37 has a considerably higher reaction threshold than the US compositions. However, the firing protocol, which required unreacted vehicles to be re-impacted, destroyed any mechanistic information on the ignition process. Based on the UK experiments it is probable that the EDC37 flowed away from the point of impact. Residual explosive pinched between the front and rear faces of the vehicle did not release sufficient energy to blow-off the cover plate and would have been characterised as ‘no reaction’. It is slightly surprising that a threshold was eventually established and merits further investigation.

In EDC37 experiments which included annular gaps the explosive was able to flow more freely and the pinch threshold was further reduced.

Impacts with the flat nosed projectile showed similar mechanical behaviour of the explosive below the pinch threshold. Material attempted to flow around the projectile and distend the cover plate. However, as shown in calculations in figure 8, the explosive ahead of the projectile could not easily flow around the edges of the projectile and was compressed. The pinch threshold for newly manufactured and aged material appeared to be comparable. It is postulated that this was due to the comparable mechanical properties of the highly compressed material ahead of the projectile.

Following pinch, reaction was sufficient to blow-off the cover plate but did not result in a significant overpressure. Ignition marks on the vehicle and the large quantities of ejected explosive seen around the target area suggest that reaction was largely confined to the region under the projectile.

Impacts onto mechanically loaded explosive samples have shown a different failure mechanism with an apparent shattering of the explosive leading to slightly more violent reactions. Results from the few experiments undertaken in this geometry indicate that the aged explosive may be less susceptible to this failure mode. Work has been initiated in a joint collaborative programme between AWE, the US DOE laboratories and the Cavendish laboratory at Cambridge to develop an improved understanding of the internal processes occurring in the explosive during impact [7].

LANL studies have shown that the impact process converts beta-phase HMX to the more sensitive delta form. Their studies have used laser illumination and the second harmonic generation properties of the delta-phase crystals to detect its formation. X-ray spectroscopic analysis is in progress on samples recovered from UK impact tests. Differential scanning calorimetry has been performed to examine the phase transition region. Figure 10 is a trace from a run at 10°C per minute for two samples. Samples retrieved from impacted material have shown a depression of the endotherm for the transition by about 20°C. This is still under investigation but one theory suggests that the depression is indicative of delta phase HMX autocatalysing the phase transition of the bulk material. Unexpectedly, the transition depression was found in all parts of the impacted samples and was not restricted solely to the area of impact.

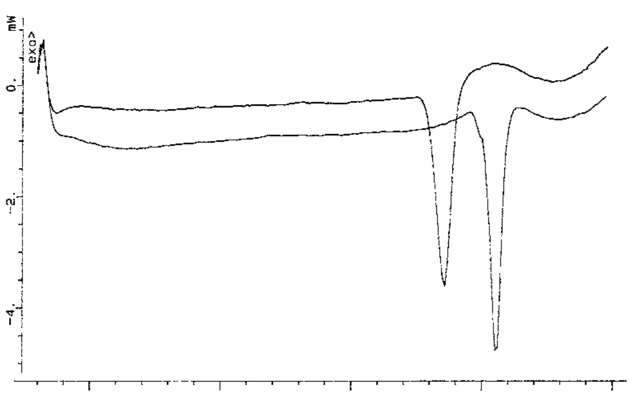

Figure 10 DSC analysis for impacted and pristine explosive samples

Conclusions

LLNL have conducted Steven tests on EDC37 that have shown the material to have an extraordinarily high threshold for detectable ignition in their test configuration relative to other HMX based compositions. Violent reactions have not been observed.

In this paper experiments have been reported for EDC37 in a geometry closely based on the Steven test. Results indicate that ignition occurs when the explosive is pinched between the front cover plate and the rear inner surface of the vehicle.

Experiments with round nosed projectiles to compare the response of aged and unaged EDC37 have shown that aged material has a significantly lower ignition threshold. It has been postulated that this is due to the degradation of the nitrocellulose in the binder which results in a lower viscosity for the explosive under the test conditions. The aged material is able to flow away from the impact more easily. In all cases ignition did not grow to violent reaction.

The reduced resistance to round nosed impact of aged EDC37 and therefore greater likelihood of a pinch ignition could not have been easily predicted from quasi-static mechanical testing and needs to be considered when developing safety assessments for handling operations.

Flat nosed impacts did not show the same age related threshold ignition dependency.

Unaged mechanically loaded samples appeared to fail in a brittle fashion and were not dependent on pinch for ignition.

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