Article

Studies of XDT phenomena under fragment impact conditions

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Abstract

In this paper we present the results of our experimental studies aimed at understanding the conditions under which XDT may occur as the result of fragment impact, and elucidating the mechanism(s) responsible. We have used a 30 mm powder gun to launch a variety of projectiles at velocities up to ca. 2100 m s^{-1} at a range of explosive targets. In particular, we have studied the necessary conditions for XDT to occur when energetic material is free to expand across a void before subsequent re-compression / re-shock against a surface. We have shown that under certain conditions XDT can occur with cast-cured and pressed PBX's as well as traditional melt-cast materials. We discuss the implications of these results with respect to the mechanism responsible for XDT, and also the relevance to weapon safety.

Keywords: XDT

1. Introduction

Fragment and bullet impact pose a serious threat for many weapon systems because of their potential to induce violent reactions in the energetic materials (explosives and propellants) contained within them. For detonable materials (explosives and some propellants) the most obvious hazard is that arising from a prompt Shock to Detonation Transition (SDT). For some energetic materials, in strongly confined weapon systems, it is also possible for a burning reaction (induced by the initial stimulus) to accelerate and produce a violent event. When this deflagration transitions to a detonation the event is referred to as a Deflagration to Detonation Transition (DDT). However, in some scenarios detonations have also been observed under conditions insufficient to cause SDT or DDT. These events have been labelled XDT (X for unknown, Detonation Transition).

Delayed events such as DDT and XDT are of considerable importance in assessing hazard scenarios as the threshold energies required are usually considerably less than those necessary for prompt shock initiation. It has generally been assumed that XDT arises as the result of some combination of damage to the energetic material and re-shock or re-compression of this damaged material. However, the mechanism is not well understood, and to date no predictive capability for XDT exists.

Over many years we have carried out a large number of experimental studies of projectile impact into secondary explosives[1), 2)]. Originally, these experiments were designed to study SDT events, but during the course of the work a number of XDT events were observed and our preliminary findings were reported[3)]. These have now been studied in greater detail, with a wider range of explosive materials, to provide improved understanding of the mechanism responsible and reliable data which can be used for future modelling efforts. The results and interpretation of these experiments are described in this paper, together with a discussion of the implications for weapon safety.

2. Experimental details

Over the last few years several hundred projectile impact experiments have been carried out to investigate XDT processes. In this paper we give only a summary of the important observations, together with details of the most recent work.

The experiments were carried out using unconfined cylindrical charges of the test explosives. All impacts were carried out on the flat front face of the charges, which in some cases was bare and in others was covered by a barrier plate (PMMA, aluminium or steel). The majority of

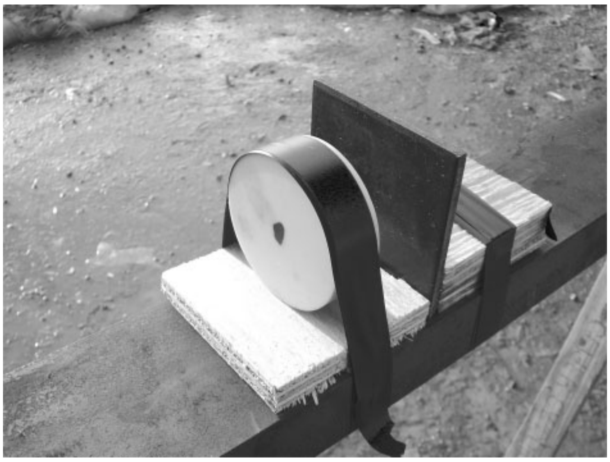

Fig. 1 Test charge arrangement.

charges were 100 mm long and 57 mm in diameter, although some materials were tested at different dimensions. The experiments were designed so that the shocks generated on projectile impact were below the threshold conditions for SDT. However, the charges were positioned such that after projectile strike the expanding explosive material would impact a rigid surface placed a short distance away. In some experiments we investigated the effect of the charge expanding radially and impacting a steel support beam beneath it, and in others the charge was allowed to expand longitudinally before impacting a plate or another explosive charge placed to the rear. A typical charge arrangement is shown in Fig. 1.

Experiments were carried out using both flat-ended and conical-tipped projectiles, all with a diameter of 13.15 mm. The projectiles were made from hardened steel, housed in a nylon sabot and fired from a rifled 30 mm RARDEN gun. This arrangement allowed velocities in the range 400 - 2000 m s^{-1} to be studied with very few projectile stability problems. In our earlier work firings were filmed with a Fastax high-speed cine camera, fitted with a quarter height block, framing at ca. 30,000 pps. In our more recent experiments, described in this paper, we have used a Phantom 7 high-speed video camera (typically with a framing rate of 90,000 pps) to observe the events. The high-speed imaging was used to determine projectile velocities, to check on projectile stability and study the charge expansion and initiation of XDT.

3. Results

3.1 General observations

Analysis of all the XDT experiments we have conducted has allowed us to make some general observations:

- XDT was never observed in confined charges, where the expansion of the explosive is suppressed.
- XDT was only observed when the explosive was free to expand and impact a secondary surface.
- The separation of the charge and secondary surface was found to be critical. At the scale of our experiments a separation of ca. 25 mm appeared to be the most likely to produce an XDT response.
- The high-speed photographic records showed that initiation of XDT was always at the interface between the damaged explosive and secondary surface.
- Any delay between impact on the secondary surface and initiation was less than the inter-frame time of the record (ca. 11 μs for the Phantom 7 records).
- In experiments which produced an XDT event the impact velocity of damaged explosive on the secondary surface was ca. 300 - 500 m s^{-1}.

These general observations led us to the hypothesis that XDT arising from projectile impact was the result of re-shock / re-compression of damaged, and thus more sensitive, explosive against a secondary surface.

We have observed XDT in 8 different explosive compositions which span the main types of secondary explosive in common use. These are listed in Table 1, and throughout the rest of this paper will be referred to by the code letter given in this table. Compositions A and B are both melt-cast explosives which are naturally brittle, and not surprisingly we have found them to be very susceptible to XDT, initiating on either radial expansion against the steel sup-

Table 1 Compositions.

Code	Composition	Comments
A	RDX 60 % / TNT 40 %	Melt-cast
B	HMX/RDX 75 % / TNT 25 %	Melt-cast
C	RDX 88 % / Grease 12 %	Mouldable demolition explosive
D	RDX 85 % / HTPB 15 %	Cast-cured PBX
E	HMX 92 % / HTPB 8 %	Cast-cured PBX
F	RDX 63.2 % / Al 20 % / K10 6.8 % / Diorez&MDI 10 %	Cast-cured aluminised PBX
G	HMX 95% / HTPB 5%	Pressed PBX
H	HMX 91 % / K10 8 % / NC 1 %	Pressed PBX

port beam or longitudinal expansion against a steel back plate. It is generally true to say, that the mouldable demolition explosive and the cast PBX's, as a class, were somewhat more resistant to XDT than the melt cast explosives in that they required a higher projectile impact velocity. They also appeared to be more specific in that compositions C, D and E appeared to only undergo XDT on impact with a rear plate, whilst composition F only appeared to initiate on radial expansion against the support beam. The reasons for this behaviour are not clear at the present time, and clearly warrant a more detailed study. In all our experiments to date we have only observed XDT with flat-ended projectiles when a cover plate was used with sufficient thickness to eliminate the pseudo 1-D shock, which otherwise resulted in SDT. However, with conical-tipped projectiles, which have a significantly higher threshold velocity for SDT, XDT was observed with uncovered charges. Our most recent experiments, which we discuss in detail here, have looked at two pressed PBX's with high nitramine loading (compositions G & H). The results for these compositions are discussed in more detail below.

Compositions G and H are similar high performance pressed PBX's differing principally in the binder system employed. Due to the high HMX loading of the formulations they are both sensitive (low threshold for SDT) and brittle.

Only 3 XDT tests were carried out with composition H, all involved bare charges (60 mm diameter × 20 mm thick, density = 1830 kg m^{-3}), a steel plate 25 mm behind the charges, and projectiles with 150° conical tips. The 3 tests differed only in the projectile velocity, and all resulted in XDT events. The slowest projectile velocity was 688 m s^{-1} and the ejected material at the rear of the charge was estimated to have a velocity of 480 - 490 m s^{-1}. It is interesting to note that the SDT threshold for this explosive with a flat-ended projectile (of the same diameter) is ca. 800 m s^{-1}, and hence even the combination of a bare charge and a flat-ended projectile may produce XDT events below the SDT threshold with this explosive.

A total of 17 tests were carried out with composition H. For these tests the charges consisted of 50 mm × 50 mm cylinders of average density 1692 kg m^{-3}. A number of different arrangements were used for these tests, although all involved two explosive charges (to represent a charge cavity). In a number of the tests the front charge (which was impacted by the projectile) was bare and a second charge was placed behind at a distance of 12.7, 25.4 or 50.8 mm. Using 150° conical-tipped projectiles XDT was observed when the gap was 25.4 mm, but not at 12.7 or 50.8 mm. A similar result was obtained when the front charge was covered with a 3 mm steel barrier plate. XDT events were also obtained in tests involving a more complex arrangement consisting of steel front cover plate (both 3 and 5 mm were used), front charge backed by 1 mm aluminium, an air gap, and a second charge covered with a 1 mm aluminium plate. Using 120° conical-tipped projectiles XDT was again observed when the gap was 25.4 mm. This arrangement was chosen to be analogous to the situation in the cone region of a shaped charge warhead, and the results consequently suggest a potential XDT hazard for weapons of this kind.

3.2 Examples

By way of illustration, Fig. 2 is a selection of frames from the high-speed video sequence of a test with composition H. The frames show the onset of initiation just after impact of the damaged explosive on the rear plate. Relative to the first frame the subsequent frames are at: 113, 226, 288, 298 and 308 μs respectively.

4. Discussion and conclusions

Our latest experiments have led further support to the hypothesis that the XDT mechanism operating under projectile impact conditions can be considered a two-stage process. The first stage is the creation of damaged, more sensitive, energetic material, and the second is initiation of the damaged material by re-shock / re-compression. For this mechanism to operate it is clear that we require the following conditions:

- A sufficiently fast impact (but below the SDT threshold conditions) to create rapidly moving damaged material.
- A space into which the damaged material can accelerate.
- A secondary surface to create re-shock / re-compression.

Analysis of the high speed records shows that for all the explosives we have studied the material being ejected against a secondary surface needs to be travelling at ca.

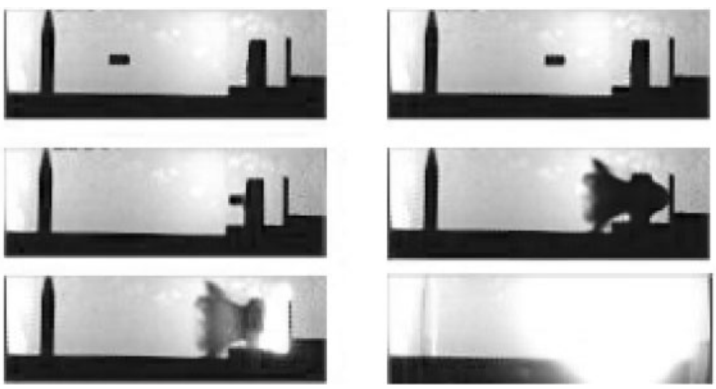

Fig. 2 Initiation of XDT.

300 - 500 m s^{-1} to produce an XDT event. This clearly indicates the extreme sensitivity of the damaged material. The lack of any significant difference in the critical velocity for the ejected material between the different types of explosives indicates that their sensitivity, once dynamically damaged, is little different. However, the lower projectile velocities required to achieve the critical conditions for melt-cast and pressed PBX's suggests, not surprisingly, that these materials are more easily damaged than the cast-cured PBX's.

It is obvious from these results that XDT could pose a significant hazard by offering a route to full detonation at significantly reduced critical stimulus levels. Whilst the experiments carried out in this study have concentrated on projectile impact, any form of stimulus which results in significant damage to the energetic material may, in principle, initiate an XDT event, provided the geometric configuration offers the opportunity for a re-shock. A weapon whose explosive or propellant filling was able to expand into adjacent spaces would naturally be particularly vulnerable. The central bore in rocket motors is a particular case which is known to exhibit this hazard.

The qualitative understanding of the XDT process which has arisen from this work should be of help in the engineering design of systems. However, further progress will be dependent on the development of a quantitative modelling capability. This is a difficult task as it requires both a model for the material properties of the explosive at high rates of strain, and a model for the shock sensitivity of the damaged material.

References

1) M. D. Cook, P. J. Haskins, and H. R. James, "An Investigation of Projectile and Barrier Geometry Effects on Impact Initiation of a Secondary Explosive", in: "Shock Compression of Condensed Matter 1991", Elsevier Science Publishers B. V., Netherlands, edited by: S. C. Schmidt, R. D. Dick, J. W. Forbes, and D. G. Tasker, (1992).
2) M. D. Cook, P. J. Haskins and H. R. James, "Projectile Impact Initiation of Explosive Charges", 9th Symposium (International) on Detonation, Portland, OR, USA, (1989).
3) P. J. Haskins and M. D. Cook, "Studies of XDT produced by Projectile Impact of Secondary Explosives", 28th Annual Conference of ICT, (1997).