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Investigation of the Process of Deflagration-to-Detonation Transition (DDT) in Granular Secondary Explosives with High-Speed Photography

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ABSTRACT

The deflagration-to-detonation transition (DDT) in confined charges of granular secondary explosives has been investigated with high-speed photography. Specially designed steel confinements, which incorporate slit windows to allow streak photography, were constructed to house pressed pentaerythritol tetranitrate (PETN) charges of known density. The results indicate that convective burning is only important during the initial stages of the DDT process in causing rapid pressure build-up, and does not govern the deflagration process up to the point of DDT. Following convection, the propagation of the combustion front was found to be governed by the compaction wave generation of hot-spot ignition sites. The transition to detonation is finally attained when the front of a plug of highly compacted material, essentially a second compaction wave formed at the combustion front, overtakes the first compaction wave and causes shock initiation of the uncompacted, and therefore, more highly shock sensitive, original-density PETN. The detonation then propagates to the end of the charge at constant velocity and a rearward shock propagates upstream through the highly compacted plug material and intersects the combustion front. The proposed mechanism is supported by the observed deformation of the internal surface of the steel confinement.

1. INTRODUCTION

An understanding of the deflagration-to-detonation transition (DDT) phenomenon in secondary explosives and propellants is important for the safe handling, storage and design of energetic materials and munitions. Controlled deflagration in propellants and accidental fires in explosives stores often result in a transition to detonation with disastrous and costly consequences. Not only would a clearer understanding of the DDT mechanism help to avoid such unwanted detonations, but it would also aid the design of'safe' components which provide a reliable detonation output. An obvious example of such a component is the electrical detonator, in which a reproducible transition to detonation in a secondary explosive would obviate the need for a primary explosive, an obvious source of hazard.

The generally observed features of the DDT mechanism in porous secondary explosives are: ignition, an accelerating combustion front, the onset of detonation at some point at or downstream from the combustion front, and sometimes a retonation propagating back towards the point of ignition. The mechanism by which detonation is initiated from an accelerating deflagration is by the formation of a shock of critical strength[1]. It is the mechanism of this shock formation which requires clarification.

It was once thought that the propagation of the combustion wave from ignition to the point of DDT was governed by a convective mode of heat transfer[1] . More recent studies[2,3] have indicated that convection is only important immediately after ignition and then propagation becomes governed by a compressive heating mechanism. The breakdown of convective flow is due to the collapse of the porous charge as a consequence of the rapid initial pressure build-up. The propagation of reaction is then governed by the formation of ignition sites in the leading compaction wave. Also known as 'hot-spots', these localised regions of heating caused by mechanical deformation have been well researched[4,5]

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and shown to be important in the propagation of reaction in energetic materials.

In contrast to porous explosives, the propagation of deflagration in cast propellants and explosives is governed by a layer-by-layer conductive burn, due to the impermeability of the charge. This mode of burning has been shown[6-8] to be insufficient to produce the pressure build-up required to form a shock of critical strength. It is only when a degree of porosity has been introduced, for example, from thermal stress-induced fissures in the material, that the pressure can increase from convective burning to form increasingly strong stress waves which coalesce downstream in the cast material to form a shock of critical strength.

In porous materials, the formation of a critical strength shock wave due to the coalescence of stress waves has been shown[3] to be unrealistic due to their more dispersive nature. Instead, the compaction-driven combustion wave becomes the source of stress waves of increasing strength which eventually cause the compacted bed to further collapse to near theoretical maximum density (TMD) at a point downstream where the intergranular pressure, due to the onset of reaction from hot-spots, is exceeded. This highly compacted region, termed the 'plug', is then accelerated by the upstream combustion front until the leading edge attains a shock velocity and pressure sufficient for a shock-to-detonation transition (SDT) in the material immediately downstream.

This study attempts to examine the existence and importance of this compaction effect in propagating the reaction front to the point of DDT, and its role in the formation of a shock of critical pressure which will initiate detonation.

2. EXPERIMENTAL METHOD

The DDT process was recorded with high-speed streak photography. An Imacon 790 image-converter camera was used. Granular pentaery thritol tetranitrate (PETN) of particle size 180 µm was pressed incrementally into the confinement such that the height of each pressed increment was less than the charge diameter. This was done to minimise the formation of density gradients within each increment. The configuration of the confinement can be seen in Fig. 1. In a previous study[9] of the DDT in 1-(5-cyanotetrazolato) pentamine cobalt (III) perchlorate (CP) the confinement was constructed entirely from polycarbonate. This explosive has a very low shock initiation pressure (for a secondary explosive) and underwent DDT when confined within this low-strength transparent material. The shock initiation pressure of PETN, although relatively low for a secondary explosive, is higher than that of CP and therefore required a confinement made from a material of higher yield strength. Mild steel was chosen for this purpose and a 1 mm slit window was fitted to allow high-speed photography.

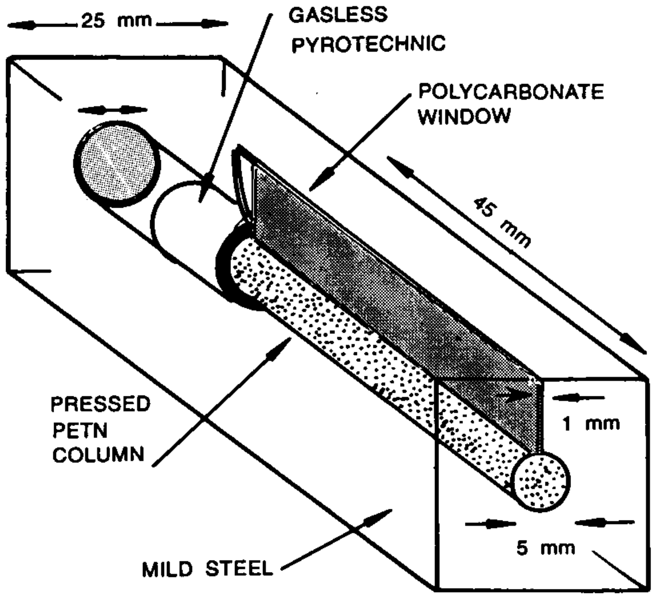

Figure 1. **The configuration of the confinement designed for the study of the DDT process in pressed granular PETN.**

The explosive column was ignited with a virtually gasless pyrotechnic mixture of boron and potassium dichromate. When ignited with a bridge-wire, the burn-front in the pyrotechnic would impinge on the end of the explosive column and cause ignition in a planar fashion which is not possible with a hot-wire in direct contact with the explosive. The confinement was longitudinally clamped between two heavy steel blocks which were connected with two high-tensile steel bolts to prevent rear-venting of the product gases. The confinement was then placed inside a vented firing-box which was fitted with polycarbonate windows to allow photography while protecting the camera from fragments.

The camera was triggered by positioning a fibre-optic probe near the start of the explosive column.

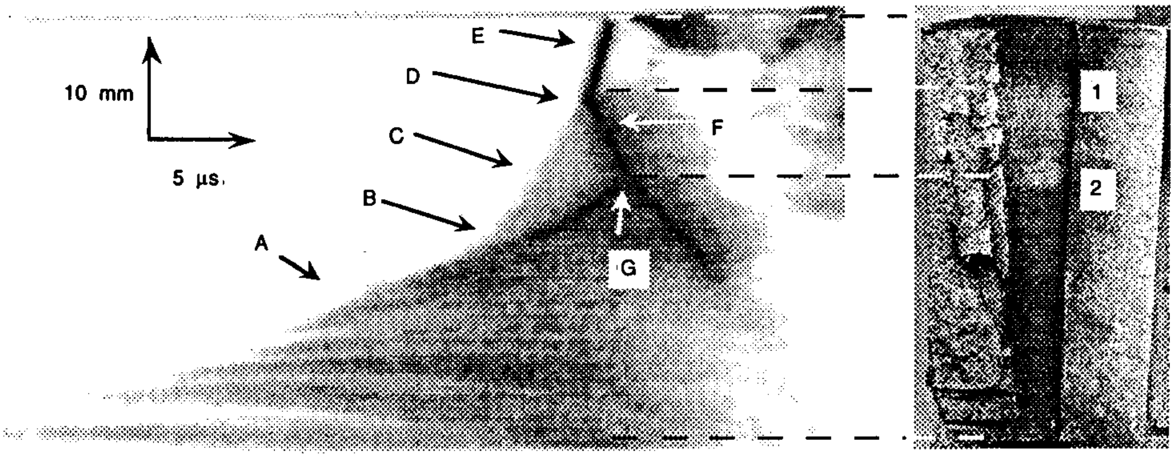

Figure 2. Streak photograph of the DDT in 79% TMD PETN showing confinement deformation at the same scale.

The light emitted from the early stages of the explosive burning would cause an output voltage from a photodiode which in turn would then be used to trigger the camera once a pre-programmed trigger voltage had been exceeded. The writing length of the polaroid film used was approximately 70 mm, which, when used at a streak speed in the range of 500-1000 ns mm^{-1}, gave a total writing time of 35 to 70 s. The photographs were digitised through computer scanning to enable accurate measurements to be made of the velocities and the lengths of the various stages of the DDT process.

In addition to the information recorded photographically, evidence of the nature of the burning processes occurring down the column could be deduced from the internal surface deformation and colouration. This technique has been used before[1,2,10] to support other experimental evidence obtained from the DDT process. For example, the run-to-detonation length deduced from the high-speed photograph has been found[11] to be in close agreement with that obtained from the point of maximum widening on the internal surface of the steel confinement.

3. RESULTS

3.1 Ignition of Uninterrupted PETN Charges

The DDT in an uninterrupted single density column of pressed PETN (79 per cent TMD) can be seen in Fig. 2. Upon ignition, the deflagration (A) propagates at a velocity of 0.9 mm μs^{-1}. A subsequent luminous front (C) then propagates from point (B) at 4.2 mm μs^{-1} and appears to accelerate until the point of DDT at (D). From (D), the detonation (E) propagates to the end of the column at constant velocity, and a rearward wave (F), possibly a retonation, propagates upstream at 4.4 mm μs^{-1}. The velocity of this wave then slows to 2.9 mm μs^{-1} upon intersection (G) with the initial burning front (A), where a reduction in luminosity also appears. The streak photograph can be directly compared with the deformation of the internal surface of the steel confinement. The point of DDT, (D), correlates closely with the point of maximum bore widening (1) which is also identifiable by the end of a light shaded region, the start of which (2) correlates closely with the point at which the rearward wave intersects the initial deflagration locus (G).

The structure of this streak record provides evidence which supports the hypothesis of plug

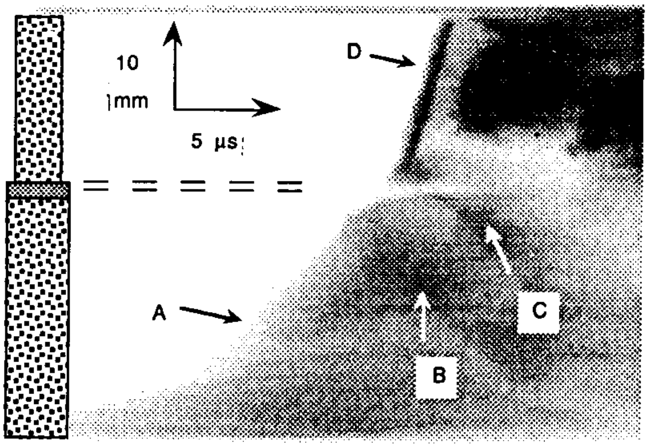

Figure 3. The streak photograph of the effect of a steel barrier on the DDT process in 80% TMD PETN.

formation and therefore the importance of compaction. The accelerating front (C) reaches a velocity comparable with the shock velocities measured by McAfee[3] (in HMX) which correspond to the front of a plug of highly compacted material. This is supported here by the rearward wave (F), which would correspond to an upstream shock propagating through the highly compact plug of PETN. Upon reaching the combustion front (A) at (G), the shock slows as it is now propagating through lower density material which has also undergone a high degree of decomposition. Unlike McAfee's results, where the detonation slows upon overtaking initial compaction wave, the detonation maintains a constant velocity to the end of the charge. This can be explained by consideration of the locus of the initial compaction wave in PETN; the shock front (C) will be propagating at a greater velocity than this initial compaction wave and therefore will overtake it. When it does it will encounter material of a lower density, i.e. having a higher void fraction, which will consequently be more sensitive to shock initiation. The shock-to-detonation transition will then occur at this density discontinuity, thus explaining the constant velocity detonation from this point to the end of the charge. In order to provide evidence to support this mechanism it is necessary to test the nature of the initial deflagration.

3.2 Ignition of PETN Charges Containing Inert Barriers

It is anticipated that upon ignition, the deflagration propagates initially due to a convective heat transfer mechanism. Subsequently, the reaction is propagated due to a compressive ignition caused by the passage of a compaction wave. To test this hypothesis, inert barriers were incorporated into the charge at positions where a particular mode of burning was expected. If the propagation of reaction is governed by convection, then by placing a steel barrier in the charge, the reaction would be expected to be halted. The effect that a hardened steel barrier, which has been lodged in place at a discontinuity in the bore width, has on propagation of reaction through 65 per cent TMD column of PETN can be seen in Fig. 3.

The barrier did not prevent the propagation of the combustion front (A) and DDT occurred within a couple of millimetres of the downstream side of the barrier. This indicates that convective burning is not governing the process leading up to DDT. In support of the role of compaction, a reflected wave (B) from the barrier indicates that a compaction wave is propagating only a few millimetres ahead of the luminous reaction front. A second rearward wave (C) emanating from the point of DDT propagates at a similar velocity to (B) which indicates that this is also a shock wave propagating upstream through the barrier and the compacted PETN.

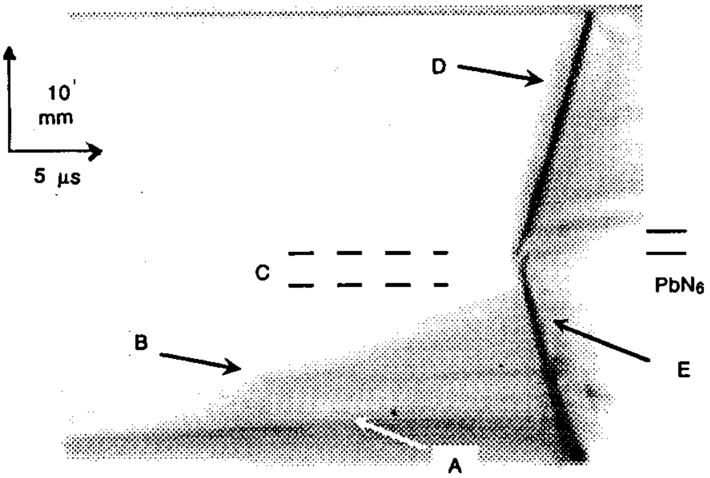

Figure 4. The inclusion of lead azide into a 55% TMD column of pressed PETN to indicate the locus of the leading compaction wave with respect to the combustion front.

When impermeable steel barriers were placed within the first few millimetres from the start of the column, the combustion front did not propagate beyond them. Barriers which were placed at distances greater than approximately 5 mm from the igniter did not hinder the propagation of the combustion front. This indicates that convection is occurring, but only during the initial stages of pressure build-up.

3.3 Inducement of DDT by Inclusion of Lead Azide

From the previous two sets of experiments, it can be seen that compaction plays an important role in the acceleration of the combustion front to produce a shock of velocity and pressure capable of initiating detonation. The locus of the leading compaction wave, relative to that of the luminous combustion front, can be shown by placing a small amount (~0.05 g) of primary explosive (e.g. lead azide - PbN_6) at a known distance from the igniter in the pressed PETN column. The result of the effect of lead azide positioned within a 55 per cent TMD column can be seen in Fig. 4.

The initial convective burn (A) propagates at 0.12 mm μs^{-1}; the subsequent faster compressive burn (B) accelerates to a velocity of approximately 0.8 mm μs^{-1} when the leading compaction wave, shown here by the leading distance (C) of approximately 4 mm, reaches the 2 mm section of lead azide (PbN_6). Detonation in the lead azide (4 mm μs^{-1}) propagates into the remainder of the pressed PETN, and the consequent detonation (D) then propagates at a constant velocity of 5.4 mm μs^{-1} to the end of the column. A further indication of the occurrence of compaction is that the retonation (E) initially propagates upstream at a velocity of 7.1 mm μs^{-1}, which is higher than the downstream detonation. This detonation velocity corresponds[12] to a density of approximately 80 per cent TMD which indicates the degree of compaction which has occurred. The retonation (E) slows as it intersects the initial convective burn locus (A), suggesting that there has been a greater degree of decomposition and consequently a lower average density.

Simultaneous initiation of an electrical detonator at the downstream end of the charge (opposite end to the igniter) has also been tried to highlight the variations of density when the upstream propagating detonation encounters the compaction wave/combustion front complex after normal ignition. The velocity of the upstream detonation was not seen to vary by any significant extent and therefore this approach was not pursued. The inclusion of lead azide to highlight the compaction process effectively works by the same principle and has the advantage of providing an *in situ* method.

4. CONCLUSION

DDT in granular secondary explosives has been shown to depend strongly upon the propagation of a compressively driven reaction front. The leading compaction wave reduces the void fraction of the charge and generates hot-spot ignition sites. The energy released from these localised areas propels the compaction wave and the process becomes self-supporting. It is postulated here that the transition to detonation occurs when the front of a plug of highly compact (near TMD) material, formed at, or very close to the combustion front reaches a velocity and shock pressure capable of a shock-to-detonation transition. The front of this plug is effectively a second compaction wave. On examining the locus of the initial compaction front relative to that of the combustion wave, the transition appears to occur when the initial compaction wave has been overtaken and the shock front encounters uncompacted explosive. This would be consistent with the observation that pre-compacted explosive is less sensitive to subsequent shock initiation. For example, Bordzilovskii and Karakhanov[13] found that in shock initiation studies, the run-to-detonation lengths of pre-shocked heterogeneous explosives were approximately double that of unshocked charges.

Even though a detonation would be expected to propagate from the point of shock initiation more readily than a retonation (due to the directional nature of shock propagation and therefore the SDT process), there is further evidence of the lowering of the shock sensitivity due to pre-compaction. This can be seen (Fig. 2) from the nature of the rearward wave which propagates upstream from the point of DDT through the plug. The velocity of this wave (4.4 mm μs^{-1}), which is comparable to the downstream velocity of the front of the plug (4.2 mm μs^{-1}), is too low for it to be a retonation which would be expected to have an upstream velocity of the order of 7 to 8 mm μs^{-1} for highly compacted PETN.

The inert nature of the upstream shock is further supported from examination of the deformation and colouration of the internal surface of the steel confinement. From the point of ignition to the point where the upstream shock intersects the combustion front locus, the bore diameter has not been increased significantly (due to the yield strength of the steel not having been exceeded by the deflagration pressure) but a noticeable darkening (possibly due to oxide formation or crystalline phase change) has occurred which would be consistent with the high temperature associated with the deflagration. From this point to the point of DDT, i.e. the region associated with plug formation, there is no darkening which indicates that little or no decomposition has occurred, thus supporting the inert nature of the plug and the rearward shock. The bore width then increases to the point of DDT from where it remains constant to the end of the charge indicating a constant velocity detonation which is supported by the streak photograph. There is also darkening in this region which indicates, as would be expected, that the steel surface has been subjected to similarly high temperatures.

These results lend further evidence to the understanding that a compressive burning mechanism and consequently the concentration of potential hot-spot ignition sites is important in the DDT process in granular explosives. Processes which alter the number of potential hot-spot sites will, therefore, affect the likelihood of DDT, e.g. pre-compaction with weak shocks.

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