Experimental study on ignition reaction evolution of pressed PBX-B in long thick wall cylinder confinement

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Abstract. In order to explore the possibility of deflagration to detonation transition (DDT) of pressed HMX-based PBX inside long thick wall steel tube initiated by ignition composition, a new experiment apparatus was designed based on traditional DDT tube, in which strength at specific locations enhanced, and multichannel PDV probes and high speed photography were used to diagnose the expansion process and rupture characteristics of tube wall. Compared with the results initiated by detonator in the same explosives and confinement, the reaction durations of detonation and ignition differed by orders of magnitude; the pressure evolution measured by tube wall velocities, and the propagation process of tube wall movement were significantly different in two reaction. Analysis shows that the convective flow of reaction products along the seam between tube wall and explosives, high temperature and pressure, dominated the reaction evolution of PBX -B initiated by ignition composition under strong confinement, and appeared as laminar burning on explosive surface and structural response of confinement. There is no reaction activated in explosive bulk by the ramp wave caused by upper stream non shock initiation reaction, least of all DDT.

1. Introduction

The shock-to-detonation transition (hereinafter referred to as SDT) of pressed explosive is that the explosive bulk is heated up after adiabatic compression under the shock wave, the hot spot formed and then drives the reaction in the explosive bulk, and the thermal and mechanical effects of the reaction form the detonation wave [1]. The non-shock initiation reaction [2], which is different from the SDT, is that the initial ignition on the surface or local position of the explosive caused by heating, fragment impact, spark, friction or other non-shock wave stimulation. The subsequent reaction of ignition is related to the properties, confinements and ignition conditions of the explosive, involving many processes, complex reaction phenomena and uncertain intensity evolution trend. The possibility of deflagration to detonation transition (hereinafter referred to as DDT) in dense PBXs or solid propellants inside long thick wall steel tube is still under question.

In 1959, A Macek [3] studied DDT process of cast HMX explosive by strain gauge and ionization probe, and put forward a physical model of wave coalescence under "one-dimensional assumption". A Macek's model shows the gas–solid boundary accelerating as the burning pressure increases with the attendant pressure waves coalescence at a significant distance up the tube from the interface. The
shock wave converges in the explosive bulk and then detonates the unreacted explosive in front of wave, which results in DDT. This theory is considered to be the main DDT mechanism of dense explosives. Tarver et al. [4] improved the model and used precise and complex models to describe the combustion process of materials. Jacobs posed a significant objection though [5], and J M McAfee [2] was also very cautious in the introduction of dense explosive DDT.

In the 1980s, R R Bernecker[6] and H W Sandusky [7] performed a series of experimental studies on the DDT process of granular explosives. The DDT mechanism of the high porosity explosives, of which density slightly higher than 50% - 70% of the maximum theoretical density (hereinafter referred to as TMD), was clearly described by using the designed piston experiment by A W Campbell [8]. It was shown that the dense explosive "piston" formed by compression wave after ignition at one end of the explosive was the key to trigger DDT. The propagation process of the combustion wave front basically meets the quasi one-dimensional condition. The specific situation of explosive reaction propagation can be monitored by the probe conduction time at different positions on the DDT tube wall. A series of experiments have been conducted at home and abroad to study the reaction propagation of different high porosity explosives and even solid propellants [6–10]. However, when the combustion wave front propagates to the fully dense area (100% TMD), the "piston", since the reaction gaseous products cannot propagate through the dense explosive bulk, the linear combustion rate decreases by 20 times when the explosive density is 90% ~ 100% TMD, that is, from the convection combustion mode to the laminar combustion mode. Compared with the increasing convection combustion speed, the combustion speed is close to the stop [2]. Therefore, for the dense explosive which itself is close to 100% TMD, if according to the wave coalescence physical model of A Macvek, the reaction is performed in a slow laminar combustion at the ignited end of the explosive, if the pressure of the combustion gaseous products is to grow rapidly enough to make the compression wave in the bulk converge to form shock wave, the burning speed of the explosive itself is required to be sensitive to the pressure. Some formulations of primary charge may meet the requirements, but it is difficult to achieve for the HMX-based secondary explosives [11]. In addition, if the shock wave pressure is required to be strong enough to form shock wave in explosive bulk, then the confinement needs to be strong enough to ensure the sustained reaction of the explosive. In the DDT experimental study of HMX based high-density charge by Huang [12], Wang [13–14] and Dai [15], steel tube is used as DDT tube. However, the stress concentration will be caused when the probe holes on tube wall are under high pressure, resulting in the actual yield strength significantly lower than that of the steel tube without hole. From the point of view of the fragments of the apparatus after reaction, the damage of the tube wall is basically tearing along the probe holes. In the conclusion, Huang [12] and Wang [13–14] thought that DDT would still occur if stronger confinements were used.

In addition, according to experimental study of Shang [16], if the reaction gaseous products cannot penetrate the explosive bulk after ignition, it will propagate in the structure seam or explosive cracks in the form of convective flow, and induce the explosive surface combustion at near position after a elapsed time of induction. According to the high-speed photographic images and the pressure histories of different positions in the slot, it can be seen that when the explosive surfaces in the slot are ignited, the reaction degrees of different local positions are different, and the pressure growth is not strictly in accordance with the flame propagation direction. To realize this point, it cannot be simply considered that the conduction signal recorded by the probes represents the position of reaction propagation in explosive bulk.

It can be seen from S I Jackson’s experimental study [17], Two explosive tablets were tightly confined in thick wall steel cell to form a slot, 80 µm in the width, and then ignited from one slot end by electrically heated wire. In reaction evolution process, the flame propagated in the slot and ignited the explosive surface, which causes the pressure growth in the gap and drives the flame to accelerate forward along the gap. The highest flame propagation speed is even up to 10km/s, and the peak pressure is 680 MPa. The reaction propagation characteristics in explosive slot are similar to Leuret’s observation of "low velocity detonation" [18], and even may be mistaken as "DDT" because the propagation speed of gaseous products convection and surface combustion behaviour reaches the explosive detonation speed level. After the rupture of Jackson’s experimental apparatus, almost complete explosive samples with only surface reaction were recovered, which also confirmed that
there was no ignition into explosive bulk [17]. The experimental scale of ignition in Jackson’s slot is exactly the characteristic width of the seam between explosive pellets, and structure seam between explosive and confinement in DDT tube. The reaction results show the image characteristics of convective flow propagation in seam and cracks when the reaction gaseous products can’t propagate through the dense explosive bulk.

All kinds of evidences show that the wave coalescence physical model under one-dimensional assumption can’t explain the reaction behaviour of high-density solid explosive well after it ignites at one end under the strong confinement condition of traditional DDT tube and its similar long tube. However, the combustion and pressure increase caused by convective flow propagation of high temperature and high pressure reaction gaseous products produced by ignition on the surface of explosive in structure seam may be the main mechanism for the violent evolution of reaction.

2. Experimental apparatus and test system

In order to investigate the actual reaction evolution of pressed explosive (formulation PBX -B) after ignition at one end under the confinement of long thick wall cylindrical tube, and to explore whether DDT will occur in pressed explosive PBX -B under confinement stronger than classic DDT tube. In this paper, the single end ignition experiment (hereinafter referred to as ignition experiment) of HMX-based dense explosive PBX -B is designed by triggered with an electric igniter with black powder under specific confinement conditions.

The experimental apparatus is shown in figure 1. The steel cylinder tube is made of 45 steel with an inner diameter of 20 mm and an outer diameter of 60 mm. The total length of the apparatus is 600 mm. There is no probe hole set on tube wall to keep the structure complete and symmetrical, so as to avoid stress concentration as the weakness of structure under high pressure process, which will cause the apparatus to early failure, ensuring that the reaction in the tube will not be accidentally interrupted; the two ends of tube are added with heavy caps to prevent reaction being interrupted due to the end being rushed out; the tube wall at the joint of the end cap is provided with a round neck with gradual thickness, so as to prevent reaction early terminating by shear fracture of contact position when tube wall expanding. The dense explosive PBX -B, contains 87%HMX with a density of 1.845 g/cm3 (TMD is 1.874 g/cm3).The total length of the filled explosive pellets is 440mm. The assembly gap between explosive and tube wall is about 70–120 μm. The mass of ignition powder is about 1.75g, and the response time of ignition system is about 4ms.

![Figure 1. Experimental apparatus.](image)

In the ignition experiment, Photonic Doppler Velocimeter(hereinafter referred to as PDV), digital high-speed photography and air-blast overpressure sensors are engaged to diagnose the reaction evolution. The schematic diagram of testing system is shown in figure 2: the digital high-speed photography is used to record the experimental process image; the PDV is used to record the shell expansion speed history at different positions of apparatus. The delay synchronizer is used to trigger the ignition system, time interval recorder and digital oscillographs at different setting moments.
The positions of measuring points of PDV probes in the ignition experiment are shown in figure 3, with the interface between ignition nozzle and explosive as the reference point (0mm). The measuring points 2~7 are respectively perpendicular to the tube wall to measure the radial movement; the measuring points 1 and 8 are perpendicular to the plane of the apparatus end cover to measure the axial movement. The diagram of experimental system is shown in figure 4.

Qiu conducted the purposed detonation experiment of same format of pressed HMX-based explosive PBX-A in the same confinement before [19], which can be taken as a metric for reaction violence calibration of ignition experiment of PBX-B. The pressed explosive PBX–A conducted in detonation
experiment contains 95% HMX with a density of 1.860 g/cm³ (TMD is 1.889 g/cm³), the mechanical property and detonation performance of which is very similar with PBX-B.

3. Experimental result
The typical high-speed photographs of two experiments are shown in figure 5 and figure 6 respectively.
In the detonation experiment, because of the start-up time drifting of rotating lens high-speed photography, it is hard to ensure the moment of figure 5. It can be seen that explosive reaction gaseous products drove the cylinder tube wall fragments to fly outward, and the reaction propagated stably at detonation speed along the initiation direction, with a total reaction time of about 60 μs.

![Figure 5](image)

**Figure 5.** Typical high-speed photograph of detonation experiment of pressed PBX-A [19].

In the ignition experiment, the taking time of three pictures from top to bottom of figure 6 was at 7.317ms, 7.433ms and 7.483ms after ignition signal sent out. At 7.317ms (response time of ignition system is about 4ms after ignition signal sent out), the obvious flame appeared with tube wall expanded near the tail end. After no long than 100 μs another flame leakage from tube crack near ignition end. The expansions of tube wall are obviously not symmetrical in the circumferential direction. At 7.50ms, the flame covered the most of apparatus. The total reaction time of ignition experiment is about 4 ms, much longer than the reaction time of detonation experiment by orders of magnitude. And there is no upstream and downstream relationship for reaction front propagation and reaction intensity growth.

![Figure 6](image)

**Figure 6.** Typical high-speed photograph of ignition experiment of pressed PBX-B.
Velocity profiles measured by PDV in two experiments are as shown in figure 7 and figure 8 respectively.

In detonation experiment, the maximum expansion velocity of the radial measuring point is more than 400m/s, and every waveform has the von Neuman peak characteristic due to detonation wave front propagation.

In the ignition experiment, the moment when tube wall first began expansion is 7.20 ms after the ignition signal being sent out, and then in hundreds of microseconds, several positions of the tube wall expanded in random time sequence, deformed or even cracked, and finally the apparatus disintegrated. The starting sequence of the movement of each measuring point along the axial direction on the tube wall is 7-6-5-2-3-4, which reflects that the outburst time and position of the explosive inside the tube are random when the violent reaction started, rather than the one-dimensional propagation characteristics of detonation or DDT.

![Figure 7. Velocity profiles measured by PDV in detonation experiment of pressed PBX-A[19].](image1)

![Figure 8. Velocity profiles measured by PDV in ignition experiment of pressed PBX-B.](image2)

The results of air blast overpressure of ignition experiment are shown in figure 9. Two air-blast overpressure sensors were 1.5m away from the apparatus respectively, measured the peak pressure of air-blast wave at 9.75 and 9.80ms after ignition as 0.05 and 0.07 MPa respectively, converted to TNT equivalent weight 390g, indicating that most explosives consumed. It should be noted that the TNT equivalent weight is calculated by the explosion of bare explosive, and the conditions for the overpressure of air shock wave in the experimental results in this paper are under specific confinements, so it cannot be simply compared with TNT equivalent weight, only as reference data.

![Figure 9. Air blast overpressure profiles of initiation reaction of pressed PBX-B.](image3)
The recovered fragments in ignition experiment are shown in figure 10. The fragments formed by detonation loading are small and slender, and the size and shape are evenly distributed.

![Figure 10](image)

**Figure 10.** Recovered fragments in detonation experiment of pressed PBX-A [19].

The recovered fragments in ignition experiment of pressed PBX-B are shown in figure 11. Compared with the fragments formed by detonation loading, the size of recovered fragments in ignition experiment is significantly larger, and the shape and size distribution are uneven; there are more obvious burning patterns on the inner surface of some fragments, and there are no spallation patterns formed by detonation loading; there is no large-to-small evolution characteristics of the fragments formed by the typical DDT process from the ignition end to the far end. On some fracture surface of the tube wall the un-reacted explosive smear could be found.

![Figure 11](image)

**Figure 11.** Recovered fragments in ignition experiment. Un-reacted explosive smear could be found on some fracture surface of apparatus.

4. Analysis and discussion

4.1. Time sequence analysis of reaction evolution in ignition experiment system

The console output ignition signal is time zero. Combined with high-speed photography and PDV signal, the action time of ignition system is about 4ms, and the tube wall began to expand at 7.20ms. The equivalent pressure in the tube is less than the yield limit of tube wall. Because the first rupture was at side of the tube wall close to the background, it is hard to ensure the specific moment of the macro crack. The maximum time from the plastic deformation of the tube wall to the first rupture is not more than 100 μs. The time and location of the strong reaction (deflagration or explosion) of explosive are uncertain.
4.2. Pressure estimated
From the waveform of the velocity profiles of ignition experiment of PBX-B, the pulse front of each measuring point before the tube wall fracture lasts for tens to hundreds of microseconds, and the slope of the velocity curve of each measuring point is close, which can be regarded as the pressure level of each measuring point in the tube is close, and the maximum internal pressure before the tube wall fracture can be estimated by Lame Formula:

Internal pressure before tube rupture estimated by Lame Formula:

\[
P = \frac{b^2 - a^2}{b^2 + a^2} \sigma_\rho + \rho h \frac{\partial v}{\partial t}
\]

Assumed that the stress on outer tube wall \( \sigma_\rho \) is equivalent to tensile strength when tube wall just ruptured:

\[
\sigma_\rho = \sigma_s = 600\text{MPa}
\]

Average acceleration of local tube wall roughly calculated by slope of the velocity curve:

\[
\frac{\partial v}{\partial t} \approx 1 \times 10^6 \text{m/s}^2
\]

Density of 45 steel:

\[
\rho = 7850\text{kg/m}^3
\]

So that the internal pressure is estimated about:

\[
P \approx 637\text{MPa} < < P_{c,J} = 35.2\text{GPa}
\]

So that in ignition experiment of PBX-B, the internal reaction pressure when tube wall just ruptured is estimated about 637 MPa, which is far less than the C-J detonation pressure of pressed PBX-B by orders of magnitude, indicating that no detonation happened even when tube wall ruptured.

4.3. Mechanism analysis of pressed explosive ignition reaction evolution in long thick wall cylinder confinement
The ignition experiment results indicate that DDT does not occur with pressed explosive PBX-B even under the condition of reinforced thick wall long tube. In the case of violent reaction from the expansion and deformation of the tube wall to apparatus disintegration, the reaction pressure level in the apparatus was only no more than 1 GPa, and the pressure pulse growth front reaches tens to hundreds of microseconds, which is impossible to form shock wave in explosive bulk, so that SDT cannot be realized, which is inconsistent with the wave coalescence physical model of A Macek under one-dimensional assumption.

In addition, the random outburst time sequence in ignition experiment is similar to the disordered conduction time sequence of ionization probes in some previous DDT tube experiment of dense explosives, which might be caused by uneven laminar combustion on explosive pellet radical and end surfaces. Based on the experimental images of Shang [16], and the randomness of the start-up time sequence of tube wall expansion, the reaction pressure level and pressure growth process before the fracture of apparatus, and the burning patterns on the inner surface of recovered fragments, it shows that the actual ignition reaction process of dense explosives in confinement is that: the high temperature and pressure gaseous products propagate as convective flow in the structure seam between the explosive and the tube wall, with the pressure in the seam increases continuously, and then more high temperature and high pressure gas is produced by the surface combustion, which propagates further to the surrounding, forming a positive feedback. Besides, the choking effect of gaseous products in the seam also raises the local reaction pressure. When the pressure level causes the explosive specific surface area to increase rapidly, the reaction speed sharply increases. Then the rapid pressure increase will lead to tube wall expansion, rupture and finally disintegration.
In conclusion, the main mechanism of the reaction evolution is that the high temperature and high pressure reaction gaseous products propagates in the gap between the explosive and the shell wall in the form of convection.

5. Conclusion

Based on the experimental results and analysis, the main conclusions are as follows:

1. PBX-B has no typical DDT phenomenon after single end ignition in long thick wall cylinder, and the reaction violence is equivalent about deflagration or explosion level. The increase duration and slope of reaction pressure indicates that there is no shock wave forming in explosive bulk, so the SDT cannot be realized, least of all DDT.

2. The high temperature and pressure gaseous products will propagate in the structure seam between the explosive and the tube wall in the form of convective flow after the explosive surface ignites, which will induce the further propagation of the explosive surface combustion and reaction in the adjacent position. This process is the main mechanism of the ignition reaction of dense explosive in long tubular confinement.

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