Group of EM Safety Evaluation

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1. The Deflagration-to-Detonation Transiton

Effect of Temperature, Density and Confinement on Deflagration to Detonation Transition of an HMX-Based Explosive

The DDT (deflagration-to-detonation transition) test is an important method to evaluate the safety performance of explosives and can provide accurate evidence for safety estimation of explosives charge. In the past two decades, a lot of experimental and computational DDT investigationson explosives were carried out. Many researches demonstrated that DDT phenomena are highly dependent on the confinement and the scale of the sample. Explosives may react severely when subjected to thermalenvironment heating conditions during transportation oroperation. However, most current investigations mainly focus on DDT safety under the ambient temperature; research at varying temperatures is still very limited. Therefore, the DDT safety performance at different temperatures(e.g. 85℃, which is close to the phase transition temperature of binders in PBX-2) remains to be studied. In order to obtain the characteristics of the deflagration-to-detonation transition (DDT) of PBX-2 (an HMX based explosive) under different conditions, DDT tests were carried out as a function of charge density, temperature and shell confinement.

The schematic diagram and photograph of the DDT installation are shown in Figure 1. The test installation mainly included a DDT pipe, an electric igniter, a cylindrical explosive PBX and some electro-ionization probes.

Figure 1. Diagram and photograph of DDT installation under heating.1-Thermocouple, 2-igniter, 3-probes, 4-heating belt, 5-steel shell, 6-explosive sample.

The DDT response characteristics for PBX-2 with 53% and 99% of theoretical maximum density (TMD) were evaluated by different shell thickness confinements at ambient temperature and at 85℃. The test results with different densities, confinements and temperatures exhibited a wide range of reaction violence. Firstly, at both ambient temperature and at 85℃ under 10 and 20 mm shell thickness confinement, PBX-2 did not undergo fully DDT at 99% TMD, only a low velocity

detonation (LVD) occurred. Secondly, PBX-2 at 53% TMD underwent DDT, and significant influence on the minimum run distance to detonation by the shell confinement thickness was observed. Strong confinement is favorable for the transition of DDT but the confinement does not influence reaction degree. Thirdly, the reaction degree of PBX-2 at 85℃ was remarkably lower than that at ambient temperature. This insensitizing effect of temperature is induced by the melting and flowing of bonders which reduces the porosity and inhibits an important step of DDT, namely, high turbulent combustion.

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2. Experiment Method and Safety Evaluating of Explosive

The Development of a Confined Impact Test for Evaluating the Safety of Polymer-Bonded Explosives During Warhead Penetration

During the penetration process lasting a few milliseconds, the warhead will undertake high pressure, whose peak is on the order of 100 MPa. The explosive charge is affected by a variety of stimuli during penetration, and thus both the response mechanism and failure mode are very complex. A very short duration of hundreds of microseconds has limited the applications of traditional safety evaluation methods at small scales, such as mechanical sensitivity, bullet impact tests, and the Susan test etc., and full scale warhead penetration is limited by cost and high risk. These factors hinder an effective determination of the stability of explosives during penetration.

Previous methods have been unable to mimic such stimuli to evaluate the safety of ammunitions. Hence, new safety evaluation methods with moderate pressures and long durations to assess the stability of the explosive charges during actual penetrations are needed. Based on existing explosives safety estimation technologies and preliminary understanding of overload environments during penetration, a confined impact model was developed.

In this work, a model with such features was obtained by calculation. The effects on the state of pressure during the drop of a hammer and the size of the explosives under confined impact were studied by calculation. The correlation between the boundary conditions and the impact pressure obtained was helpful to the design of experiments. A confined impact method using the free fall impact of a drop hammer was established, where the peak pressure is more than 0.3 GPa and the elevated pressure duration is 1–3 ms. Various types of HMX-based PBX, such as PBX-9, which has a formulation of about 40wt-% HMX+AP+HTPB+Al powders, were subjected to this confined impact test to study their response characteristics. After testing we identified a set of rules that govern the response and the ignition mechanisms are also analyzed and discussed.

In order to choose a set of appropriate test parameters such as the sample size and hammer’s mass, the confined impact process of the explosive was simulated using LS-DYNA Program. The geometry is given in Figure 1, and the pressure at the location denoted by “A” was calculated with the model.

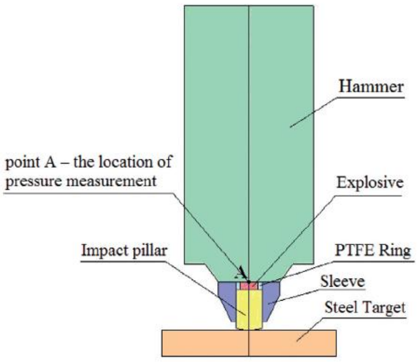

Figure 1. Geometry and labels used in the confined impact test model.

The effects of the boundary conditions on impact pressure were also calculated. The boundary conditions included the mass of hammer and the size of explosives. The 2 m drop height refers only to the results in Figure 2.

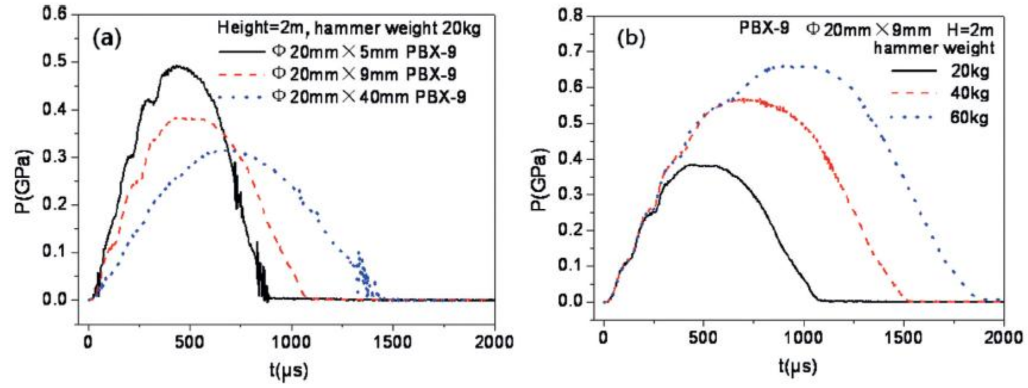

Figure 2. Simulation of pressure vs. time of impacted samples (a) of different sizes, (b) by different hammer weights.

The schematic of the test using a bomber shape hammer is shown in Figure 3. The pressure at the explosive impact surface was measured by an embedded Manganin pressure gauge, which was placed on the top of the explosive sample as shown in Figure 4. The pictures of the devices and samples are shown in Figure 5.

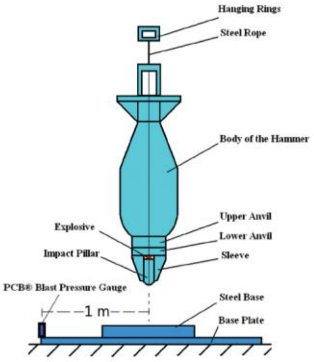

Figure 3. Illustration of drop hammer confined used for the confined

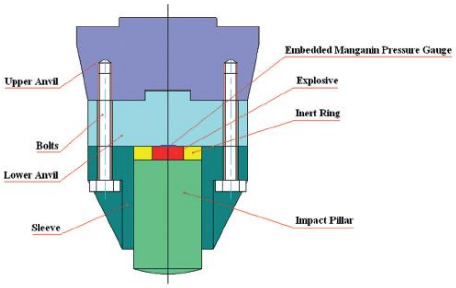

Figure 4. Detailed illustration of the device test impact Figure impact tests.

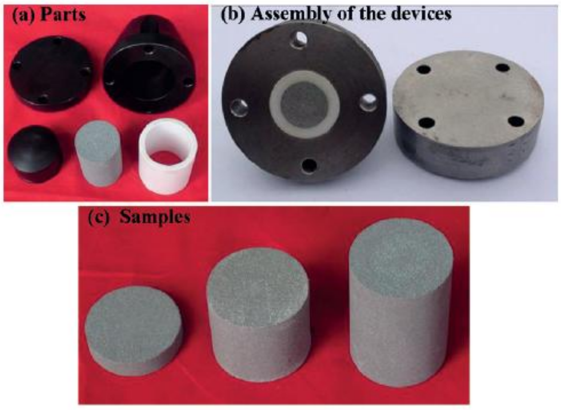

Figure 5. The pictures of devices and samples.

The results indicate that the pressure characteristics of explosives are remarkably affected by the testing conditions, such as the hammer weight and sample size. When the pressure peak is above 0.3 GP and the loading time is between 1–3 ms, decomposition and combustion occurred for the Φ20mm×5mm, Φ20mm×9mm, andΦ40mm×10mm samples. However, no reaction occurred in the test of the Φ40 mm×40 mm and Φ40 mm×60 mm samples, even during an 8 m fall. Using XPS, CT scans, as well as DSC and TG data for PBX-9, the ignition mechanism of PBX-9 was identified. All of the results herein indicate that the initial ignition of PBX-9 under confined impact is primarily due to the decomposition of AP and HTPB at low temperatures in the range of 170–200℃. Decomposition and combustion resulted in carbonization of the sample surfaces, but further reactions were not observed under the testing conditions considered. However, for a more severe scenario, the early decomposition of AP and HTPB can be the first trigger for ignition. Our study indicates that the designers of the PBX formulation should consider trying to control the early decomposition of AP and HTPB, which will allow the PBX to survive the penetration. Also, increasing the density of the explosive, adjusting the particle size and shape of AP and incorporating insensitive HMX are all potential ways to increase the extent to which PBX can survive penetration.

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Reaction Characteristic for Various Scale Explosive under Mild Impact

Impact sensitivity is one of the main indexes to evaluate the safety of explosive. Today the impact sensitivity of solid explosives is usually estimated by the Susan test and the Steven test. One cannot obtain data on inner stress and strain under loading by the Susan test, but these can be achieved by the Steven test. The shapes and sizes of explosive sample affect cook-off sensitivity and detonation performance, both of which have been widely studied. But the effects of sample scale on mild impact (velocity <120m/s) sensitivity have not been studied in detail. Furthermore, the scales of samples in standard safety tests are usually different from those in military use. Therefore, it is necessary to study the response characteristic of different scale explosives in safety tests. In order to investigate the scale effect on the impact sensitivity of cyclotetramethylene tetranitramine (HMX)-based polymer-bonded explosive (PBX)-C03 explosive to evaluate its safety in real application environments, we implemented the Steven test on various scales of PBX-C03.

A sketch map and photograph of the Steven test is shown in Fig. 1. The explosive sample embedded with pressure gauges is confined in the sample box, which is fixed in the steel base. A 2-kg steel projectile is launched by cannon to impact the sample box. Mechanical energy is converted into heat energy when the sample undergoes shock compression and shear, leading to partial decomposition, possible ignition, or even final detonation.

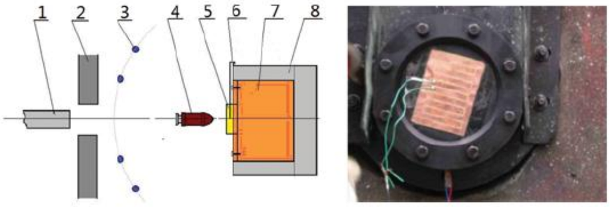

Figure 1. Outline sketch map and picture of Steven test: 1, cannon; 2, wall; 3, blast pressure gauges; 4, projectile; 5, sample box; 6, hook; 7, steel base; 8, concrete base.

The structure of the confined sample is shown in Fig. 2. It is composed of the explosive, a sample box, a steel cover, a polyethylene ring, and pressure gauges. The thickness of the box bottom and the cover are 19 and 3.5 mm, respectively. They are both made of Q235 steel. The main body of the projectile is made of 2A12 and the warhead is made of Q235 steel. The radius of spherical surface is SR31 mm. Its velocity range is 35–330m/s.

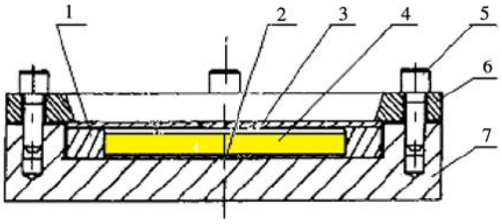

Figure 2. Structure of confined sample: 1, polyethylene ring; 2, pressure gauge; 3, cover;4,

explosive sample; 5, bolt; 6, compressive ring; 7, sample box.

The results of the PBX-C03 Steven tests show that in a certain range (larger than the critical ignition diameter and the impact projectile diameter), different diameters do not influence the velocity thresholds, but the thickness of the sample does. The velocity threshold is enhanced when the thickness of the sample increases. These studies also indicate that the mild impact-induced ignition is probably triggered by the overlapping of direct impact shockwave and reflected stress waves. Our numerical simulation results for pressure (under projectile velocities of 35.23 and 52.33m/s) and ignition times of PBX-C03 are consistent with experimental data. The knowledge obtained can be used to evaluate the safety of different scale HMX-based explosives under accidental impact or falls.

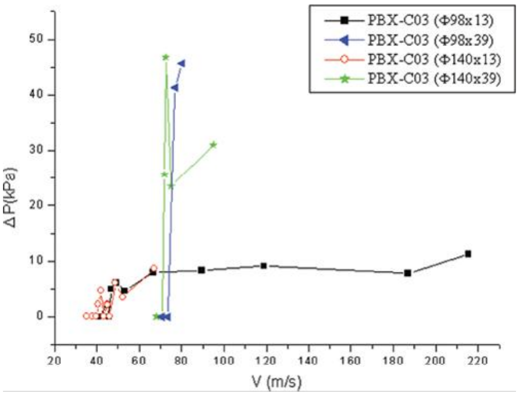

Figure 3. Correlation between overpressure and impact velocities in various scale Steven tests.

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3. Impact Ignition Mechanisms at High Temperature

Impact response characteristics of a cyclotetramethylene tetranitramine based polymer-bonded explosives under different temperatures

The impact safety and thermal safety are major concerns in evaluation of explosives safety performance. The explosives may react severely when subjected to the impact and thermal environment during such process as transportation or operation. Therefore, the issues of safety have attracted more and more attention in recent years. The explosive response in a combined thermal and impact environment is of central interest because it is difficult and there is very little data available in that regime. Most of the investigations mainly focus on impact safety under the fixed high temperatures, such as 170℃, 240℃and 250℃ up to now, the research work under various temperatures between low and high temperature, say 75 ℃, 105 ℃, 160 ℃is lacking. Moreover, most of those works concentrate on TATB-based PBX and there is little data about HMX-based PBX. It is generally considered that the safety will get worse with the increase in temperature, but in fact, the impact response may be more complex because the mechanical performance and thermal decomposition property or other properties can be distinct at different temperatures. Therefore, the impact safety performance under different heating temperatures still requires further study yet.

In this work, the safety performance of HMX-based PBX (named as PBX-2) was investigated under thermal-impact combined environment, the response characteristics of PBX-2 under different heating temperatures were obtained by high speed camera, the air shock-wave overpressure gauges, and the test methods of scanning electron microscope (SEM). These are all efficient diagnostic techniques in deflagration and detonation studies. According to analysis, it is found that the impact safety performance will be improved to some extent in the certain heating temperature range because of different response mechanisms.

Fig. 1 provides the diagram of the confined explosive specimen and embedded thermocouples. The dimension of PBX-2 sample is Φ50mm×50mm and the cover plate is 3.5mm thick and made of Q235 steel. The dimension of projectile is A20mm_20mm and also made of Q235 steel. The electric heating belt is utilized to heat the confined specimen and two thermocouples are set to measure the central and edge temperatures of PBX-2 sample.

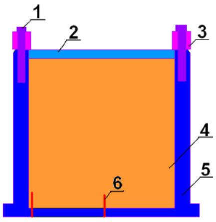

FIG. 1. Illustration of the confined specimen.

The sketch of the setup and the photograph of thermal impact coupling installation are shown in Figs. 2 and 3, respectively. At the beginning of a test, the specimen is heated to a predetermined temperature by an electric heating belt at a heating rate of 3℃/min, and then impacted by a projectile. Combined effects of heating, impacting, extrusion, and other stimulus will result in reactions of specimen at different levels. The impact safety performances of explosive before and after heated are evaluated according to the comprehensive analysis of temperature-rise process, air blast over-pressures as well as the wreckages of specimen and confinement.

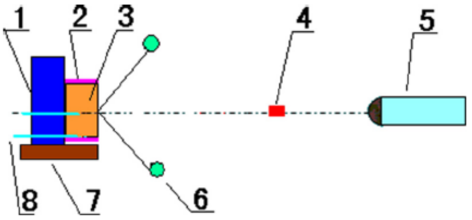

FIG. 2. Illustration of thermal-impact coupling method.

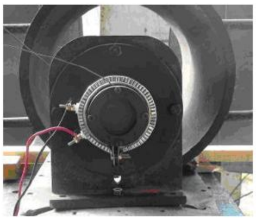

FIG. 3. Photograph of thermal-impact coupling method.

In order to investigate the impact safety of PBX-2 at various temperatures, this work focused on five cases of representative edge temperature of 28℃ (unheated), 75℃, 105℃, 160℃, 195℃with the heating rate of 3℃/min.

A dramatically dropping and rising curve of impact sensitivity was observed during the rising of temperature by the combined thermal and impact test. The results obtained in the temperature-impact velocity-ignition study have a number of implications. First of all, compared with unheated case, the impact safety of PBX-2 is improved at both 75 ℃and 105 ℃, however, at both 160 ℃and 195 ℃, the impact safety becomes significantly worse. Of all the cases, the reaction level is the highest at 195 ℃.

Second, the mechanisms of effects of temperature on impact response of PBX-2 are different for different heating temperatures: Mechanical properties has great influence on impact safety performance of PBX-2 with the temperature less than about 105℃, namely, the impact safety of PBX-2 will be improved when heated to no more than 105℃ by forming a softened, easy-flowing and energy absorbing mechanical property. When temperature rises to 160℃, impact safety is mainly affected by thermal decomposition and becomes worse. While for the case of 195℃, β→δ phase transition may become the key factor that enhances the impact safety, which gets significantly worse.

Third, in our XRD study, we find that PBX-2 with binder made from TATB has a higher β→δ phase transition temperature than those with binder made from estane and nitroplasticizer. And we guess the coexistence of b-HMX and d-HMX possesses a very high impact-sensitive.

There are still some problems require further study, such as the quantitative correlation between the phase transition rate and the impact-sensitive of HMX. It would also be valuable to either repeat the 195℃ study with the central temperature measurement, or wait at the elevated temperature long enough to equilibrate temperature across the entire sample before performing the impact experiment. This would remove the temperature uncertainty. Performing impact experiments on a room temperature but lower initial density sample would enable the attribution of increased sensitivity at 160 ℃ to increased porosity to be confirmed in a controlled way where only sample porosity is changed. Some of these studies are planned and we are going to start such investigations in the coming year.

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Fragment Impact Ignition Mechanism for Different HMX-based PBXs at high Temperature

One of the concerns in today's work with energetic materials is their safety when they are exposed to extreme environmental conditions. Hazard scenarios can involve multiple stimuli, such as heating and then fragment impact. Shock initiation of heated explosive at input pressure above 3GPa was described largely in previous studies. Impact safety for heated explosive at input pressure below 1GPa was rarely reported when XDT could occur. Impact experiments of different HMX-based PBX at high temperature were performed in this work. Compared with shock initiation results, effect mechanism of impact response for heated explosive was more complex and varied at low pressure. The results remarkably showed that impact ignition threshold velocity of heated explosive was not overall decreased with temperature elevating as expected, and it was improved on account of mechanical properties change at 75℃ -130℃. At the temperature between 190℃ and 200℃, there was a β→δ phase transition induced sharp rise of impact reaction degree for PBX with a high HMX content. In contrast to that, when the weight of HMX in PBX was less than 50% such effect of phase transition becomes insignificant. Given the hint about the importance of phase transition, the effects on such transition by 3 binders were also investigated by XRD spectrograph, respectively. An interesting binder induced temperature shift of β→δ phase transition of HMX was identified. The phase transition temperature of HMX was lifted from the range of 180-184℃ (in highly purified HMX) to the range of 190-195℃ by adding 5wt% or more binder made from TATB.

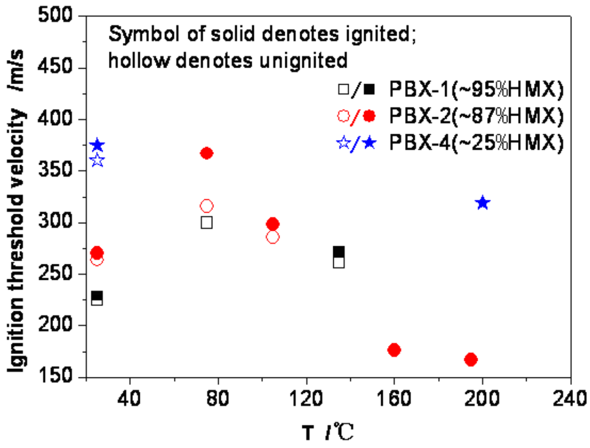

FIG. 1. Correlations between ignition threshold velocity and temperature

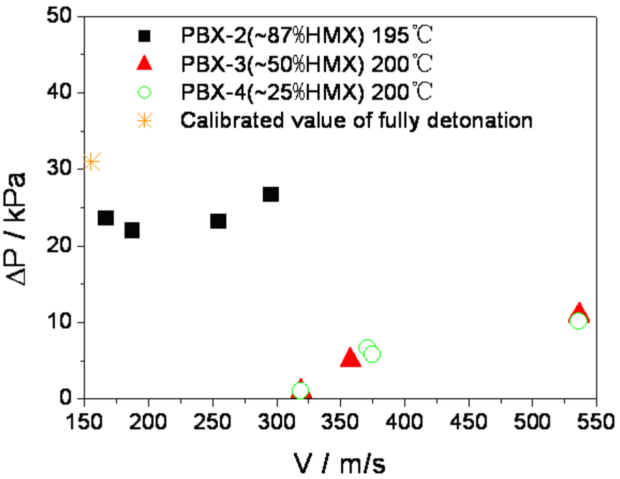

FIG. 2. Air over-pressure under different velocities of projectile at 195℃ and 200℃

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