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Shock Initiation Characteristics of Explosives at Near-ambient Temperatures

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Abstract: To study the influence extent and law of near-ambient temperature changes on shock initiation characteristics of explosives, an experimental device with local heating and cooling to explosive was designed and established. Combined with Lagrangian analysis method, the growth process of shock initiation pressure at the near room temperature from 5 ℃ to 75 ℃ for two explosives (PBX-1: a HMX/TATB composite explosive; PBX-2: a TATB based IHE) was studied. Based on the experimental results, numerical simulation of the shock initiation process for two kinds of explosives was performed by the model of ignition growth. The results show that as temperature changing from 5 ℃ to 75 ℃, the growth of shock-initiation pressure of two kinds of explosives is gradually changing fast, the run distance to detonation becomes shorter and the reaction rate parameter G_1 in the ignition growth model becomes larger, indicating that the two explosives become more sensitive to shock as near-ambient temperature increasing, the effects of near-ambient temperature changes on safety of explosives can not be ignored.

Key words: shock initiation test; near-ambient temperatures; ignition and growth reaction rate model; safety

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1 Introduction

Over the past several decades, a considerable interest has existed in studying safety aspects of heated explosives under shock. In particular, the shock sensitivity of HMX-based high explosives (HE)[1-3] and TATB-based insensitive high explosives (IHE)[4-7] under various thermal conditions has been extensively investigated. It has been widely accepted that when exposed to heat, explosives may become more sensitive to impact or to any other initiation mechanism than at ambient temperature, because a higher temperature can lead to thermal expansion or even cause phase transitions of energetic materials, thus changes in physical states (such as density, defect) of explosives occur, these may increase the "hot spots" and consequently make the explosives easier to be initiated. However, most of the previous studies mainly focused on shock sensitivity of HEs and IHEs at much higher (above 80 ℃) or lower (below 0 ℃) temperatures than ambient, the shock initiation behavior of explosives at near-ambient temperatures, the most usual environment that explosives existed in, were not adequately addressed. In this work, the experimental devices with components of heating and cooling were designed separately to investigate the effects of temperature on the shock sensitivity of two explosives (PBX-1: a HMX/TATB composite explosive; PBX-2: a TATB based IHE) over the temperature range from 5 ℃ to 75 ℃. The ignition and growth reaction rate model was employed to simulate the shock initiation processes. The main objectives here are to determine whether the near-ambient temperature changes influence the shock sensitivity of explosives. Also the work intends to provide more detailed information on the shock initiation behavior of explosives at near-ambient temperatures.

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2 Experimental

2.1 Experimental Set-up

The experimental set-up used to study the shock initiation process in explosives at various near-ambient temperatures is shown in Fig.1. A planewave lens with additional booster explosive was used to create a high-pressure shock wave in the inert materials. With the proper choice of explosive and inert materials, the pressure of the shock wave entering the test sample can be tailored. In this study, the booster explosive was a HMX-based high explosive with detonation pressure of 36 GPa. The inert materials consisted of two layers; the lower layer was an aluminum plate, which was also a part of the sample heater or cooler. The upper layer was a Teflon plate, which worked as an adiabatic layer to keep the booster explosive from heating or cooling. The sample assembly consisted of several explosive discs, gauge packages containing manganin pressure gauges were embedded between individual discs[8-11].

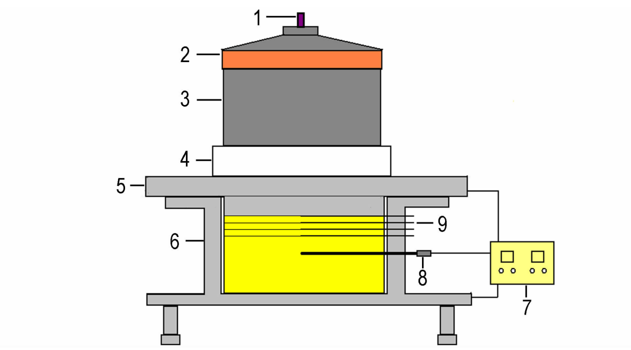


Fig. 1 Experimental set-up used to study the shock initiation process in explosives at various initial temperatures near ambient
1—detontor, 2—explosive planewave lens, 3—booster explosive, 4—teflon plate, 5—aluminium plate, 6—heater or fan cooler, 7—temperature controller, 8—themocouple, 9—manganin gauges

An electric-stove heater was used to heat the bottom and top of the explosive plates. And a gap (1.0 mm) existed between sample side surface and the heater to avoid confinement when the samples expand with heat. A thermocouple was located at the center of samples to monitor inner temperature of the test explosives. Both the heater and thermocouple were connected to a temperature controller, which could control the heat rate and ensure the sample to be heated to a preset temperature. In this work, the heat rate was about 5 ℃ · min^{-1}. For the low temperature conditions, a fan cooler was designed separately to cool samples to the temperature below ambient. Similar to the heater, the fan cooler was also controlled by the temperature controller and cool the samples at the rate of about 3 ℃ · min^{-1}.

2.2 Experimental Conditions

To study the effects of near-ambient temperature changes on the shock initiation behavior of explosives, it is necessary to make sure that the input conditions for each kind of explosive are almost the same at different initial temperatures. Table 1 shows the details of experiment information for PBX-1 (a HMX/TATB composite explosive) and PBX-2 (a TATB based insensitive high explosive).

It is clear from Table 1 that in this work the input systems of shock initiation experiments for each kind of explosive are highly uniform. The density at 20 ℃ of each material was floatation measured and had a high degree of uniformity. However, it is worth noting that the lower insert layer (Al plate), which is used to tailor the input pressure, has difference in thickness for the two explosives (a 35 mm thick Al plate for PBX-1 and a 23 mm thick Al plate for PBX-2). Besides, the shock initiation tests under four temperature conditions (5, 20, 40 ℃and 75 ℃) have carried out for PBX-1 but three temperature conditions (5, 40 ℃and 75 ℃) for PBX-2.

Table 1 Information of shock initiation experiments at different temperatures for PBX-1 and PBX-2

samples	temperature /℃	density of sample/g · cm^{-3}	booster explosive	the upper inert layer	the lower inert layer	depth of pressure gauges/mm
PBX-1	5 20 40 75	1.85	Φ50 mm×50 mm PBX9505 with density of 1.86 g · cm^{-3}	Φ50 mm×10 mm Teflon with density of 2.16 g · cm^{-3}	Φ50 mm×35 mm Al plate with density of 2.70 g · cm^{-3}	0, 3, 6, 9
PBX-2	5 40 75	1.90			Φ50mm × 23mm Al plate with density of 2.70 g · cm^{-3}	

3 Reactive Flow Modeling

The ignition and growth reactive flow model of shock initiation and detonation has been used to understand many shock initiation and detonation studies of solid explosives and propellants in several 1D, 2D, and 3D codes.[12-13] The model uses two Jones-Wilkins-Lee (JWL) equations of state, one for the unreacted explosive and the other for the reaction products, in the temperature-dependent form:

$$p_E = Ae^{-R_1 V_E} + Be^{-R_2 V_E} + \frac{\omega C_V T_0}{V_E} \quad (1)$$

$$p_P = Ae^{-R_1 V_P} + Be^{-R_2 V_P} + \frac{\omega C_V T_P}{V_P} \quad (2)$$

Where p_E and p_P are the pressure, GPa (the subscript E represent the unreacted explosive, and the subscript P represent the reaction products); V is relative volume, cm^3; T_0 is temperature of the unreacted explosive, K; T_P is temperature of the reaction products, K; ω is the Grueneisen coefficient, C_V is the average heat capacity, GPa · K^{-1}; A, B, R_1 and R_2 are constants. The unreacted explosive equation of state is fitted to the available shock Hugoniot data, and the reaction product equation of state is fitted to cylinder test and other metal acceleration data.

The reaction rate law for the conversion of explosive to products is

$$\frac{dF}{dt} = I(1-\lambda)^b\left(\frac{\rho}{\rho_0}-1-a\right)^x + G_1(1-\lambda)^c\lambda^d p^y + G_2(1-\lambda)^e\lambda^g p^z$$

$$0<F<F_{igmax};\ 0<F<F_{G1max};\ F_{G2min}<F<1 \quad (3)$$

Where F is the fraction reacted, t is time in μs, ρ is the current density in g · cm^{-3}, ρ_0 is the initial density, g · cm^{-3}; p is the pressure, GPa; and I, G_1, G_2, a, b, c, d, e, g, x, y, z, F_{igmax}, F_{G1max}, and F_{G2min} are constants. This three-term reaction rate law represents the three stages of reaction generally observed during shock initiation and detonation of pressed solid explosives[14]. Table 2 contains the modeling parameters for PBX-1 and PBX-2, and the Grueneisen parameters used for the inert materials are listed in Table 3.

4 Results and Discussion

4.1 Experimental Results

The shock initiation pressure evolution for the two explosives were measured using embedded manganin gauges over the temperature range from 5 ℃ to 75 ℃. Fig. 2 shows the measured pressure histories at the four gauge positions (0, 3, 6, 9 mm) in PBX-1 under the conditions of 5, 20, 40 ℃ and 75 ℃ respectively.

It can be found from Fig. 2 that the input pressure (the pressure of shock wave entering the test samples), which is measured by the first manganin gauges at 0mm depth, is about 10 GPa for all the four temperature conditions. The gauge records show rapid pressure increases, indicating the rapid growth of shock wave. Fig. 3 shows the peak pressure of gauges at different depth under the four temperature conditions, and Fig. 4 shows the time for shock wave running from 0 mm to 9 mm under the four temperature conditions.

Table 2 Ignition and growth modeling parameters for PBX-1 and PBX-2

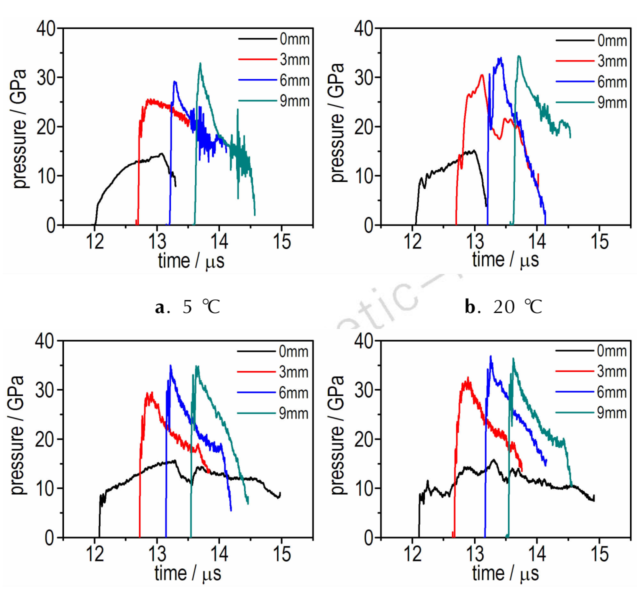
parameters	unreacted JWL	
	PBX-1	PBX-2
A/GPa	9.32×10^5	7.781×10^4
B/GPa	−5.35	−4.8
R_1	14.10	11.30
R_2	1.41	1.13
w	0.8867	0.8867
C_V/ GPa · K^{-1}	2.781×10^{-3}	2.487×10^{-3}
T_0/K	298	298

parameters	product JWL	
	PBX-1	PBX-2
A/GPa	852.4	654.67
B/GPa	18.02	7.1236
R_1	4.6	4.45
R_2	1.3	1.2
w	0.38	0.35
C_V/ GPa · K^{-1}	1.0×10^{-3}	1.0×10^{-3}
E_0	0.102	0.069

reaction rates					
parameters	PBX−1	PBX−2	parameters	PBX−1	PBX−2
a	0	0.22	b	0.667	0.667
c	0.277	0.667	d	0.667	0.111
e	0.333	0.333	g	1.0	1.0
x	20.0	7.0	y	2.0	1.0
z	2.0	3.0	I	7.4×10^{11}	4.0×10^6
F_{igmax}	0.3	0.5	F_{G1max}	0.5	0.5
F_{G2min}	0.5	0	G_1	48.0	0.48
G_2	400	400			

Table 3 Grueneisen parameters for inert materials

inert	ρ/g · cm^{-3}	shear modul/GPa	C/km · s^{-1}	S_1	S_2	S_3	γ_0	a
Teflon	2.160	2.33	1.68	1.123	2.98	−5.8	0.59	0
Al	2.703	27.6	5.24	1.4	0	0	1.97	0.48



a. 5 ℃ b. 20 ℃ c. 40 ℃ d. 75 ℃

Fig. 2 Measured pressure histories at the four gauge positions in PBX-1 under different temperature conditions

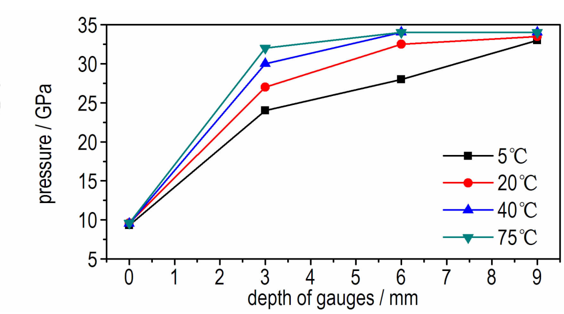


Fig. 3 The peak pressure of gauges at different depth of PBX-1 under the four temperature conditions

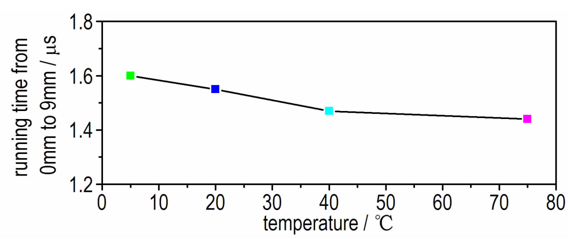


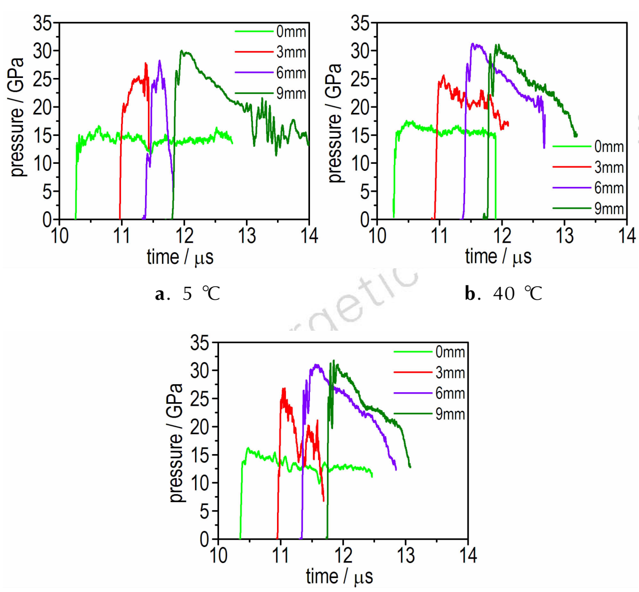
Fig. 4 The time for shock wave running from 0mm to 9mm depth of PBX-1 under the four temperature conditions

It can be found from Fig. 3 that when shock wave (or detonation wave) running to 9 mm depth of the samples, no increase in peak pressure occurs for the conditions of 40 ℃ and 75 ℃, however, for 5 ℃ and 20 ℃, the peak pressure grows to about 34 GPa, which is close to the detonation pressure of PBX-1. These results indicate that when the PBX-1 is impacted by a shock wave of about 10 GPa at near-ambient temperatures, the run distance to detonation is between 6 mm and 9 mm for 5 ℃, about 6 mm for 20 ℃ and between 3 mm and 6 mm for 40 ℃ and 75 ℃. Besides, from Fig. 4, it can be found that the time for shock wave running from 0 mm to 9 mm decreases as the initial temperature increases.

All the results above clearly show that the near-ambient temperature changes affect shock initiation characteristics of the PBX-1: as temperature changing from 5 ℃ to 75 ℃, the pressure in shock front grows more rapidly, the run distance to detonation becomes shorter, and the PBX-1 becomes more sensitive to shock. For this trend, one reasonable cause may has been that the thermal expansion with heat led to a higher concentration of voids or other defects in the samples, these can increase the "hot spots" and consequently make the explosives easier to be initiated.

Fig. 5 shows the measured pressure histories at the four gauge positions in PBX-2 under the conditions of 5, 40 ℃ and 75 ℃ respectively.

It can be seen from Fig. 5 that the input pressure is about 15 GPa for all the three temperature conditions. Fig. 6 shows the peak pressure of gauges at different depth under the three temperature conditions, and Fig. 7 shows the time for shock wave running from 0 mm to 9 mm under the three temperature conditions.



a. 5 ℃ b. 40 ℃ c. 75 ℃

Fig. 5 Measured pressure histories at the four gauge positions in PBX-2 under different temperature conditions

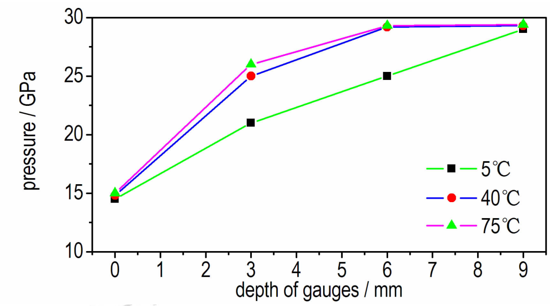


Fig. 6 The peak pressure of gauges at different depth of PBX-2 under the three temperature conditions

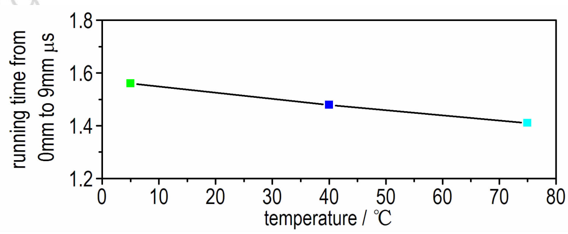


Fig. 7 The time for shock wave running from 0 mm to 9 mm depth of PBX-2 under the three temperature conditions

From Fig. 6, it can be found that when shock wave (or detonation wave) running from 6 mm to 9mm depth of the PBX-2 samples, no increase in peak pressure occurs for the conditions of 40 ℃ and 75 ℃, however, for 5 ℃, the peak pressure grows to about 30 GPa, which is close to the detonation pressure of PBX-2. And from Fig. 7, it can be seen that the time for shock wave running from 0 mm to 9 mm depth of PBX-2 decreases as the initial temperature increases.

These results also indicate that, similar to PBX-1, the near-ambient temperature changes affect shock initiation behavior of the insensitive explosive PBX-2: as temperature increasing from 5 ℃ to 75 ℃, the pressure in shock front grows more rapidly, the run distance to detonation becomes shorter, and the PBX-2 becomes more sensitive to shock.

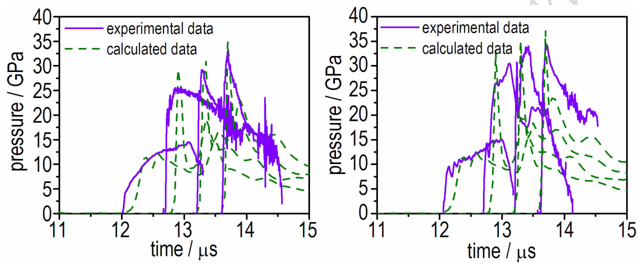
4.2 Comparison of Experimental and Calculated Results

The ignition and growth simulation of the shock initiation of PBX-1 at 5, 20 ,40 ℃ and 75 ℃ are illustrated in Fig. 8 , respectively. Fig. 9 shows the comparison of experimental and calculated results for the shock initiation of PBX-2 at 5 , 40 ℃ and 75 ℃, respectively.

From Fig. 8 and Fig. 9 it is quite evident that the ignition and growth model simulates experimental records quite well and can be reliably used to describe the shock ignition process involving high explosive PBX-1 and insensitive high explosive PBX-2 at temperature range from 5 ℃ to 75 ℃. While most of the modeling constants remain unchanged, only few of them require a change depending on the temperature. These constants are shown in Table 4.

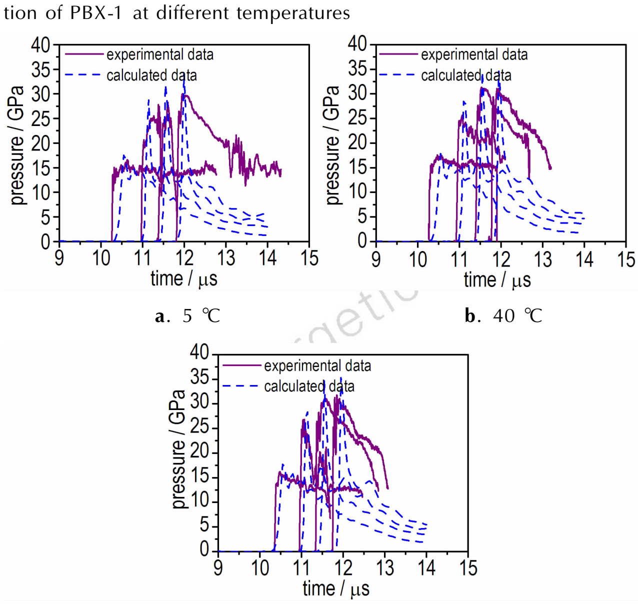
It can be found from Tables 4 that the unreacted JWL constant *B* decreases with an increase of temperature, however the reaction rate model constant G_1 increases as temperature increases, indicating that both of PBX-1 and PBX-2 react more rapidly as temperature changing from 5 ℃ to 75 ℃. This is consistent with previously published shock initiation experiments and calculations on other explosives. [3]

In contrast to the experiments, which provide limited data on shock pressure at only four positions of the samples, the numerical simulations provide more detailed information on the shock initiation processes. Fig. 10 show the calculated shock pressure profiles at various depth of PBX-1 for 20 ℃ and 75 ℃ conditions respectively. From this figure the detailed growth processes of shock waves have been clearly presented, and it can be found from Fig. 10 that the run distance to detonation is about 6 mm for 20 ℃ but 4.5 mm for 75 ℃.



a. 5 ℃ b. 30 ℃ c. 40 ℃ d. 75 ℃

Fig. 8 Experimental and calculated pressure profiles in the shock initiation of PBX-1 at different temperatures

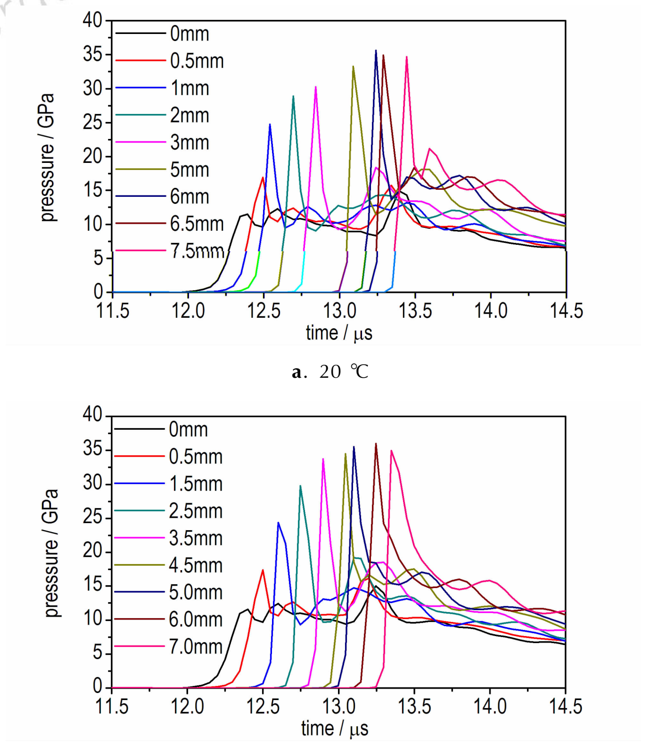


a. 5 ℃ b. 40 ℃ c. 75 ℃

Fig. 9 Experimental and calculated pressure profiles in the shock initiation of PBX-2 at different temperatures

Table 4 Ignition and growth modeling parameter changes for PBX-1 at different temperatures

explosive	temperature /℃	unreacted JWL constant B/GPa	reaction rate constant G_1 / $GPa^{\gamma} \cdot \mu s^{-1}$
PBX-1	5	-5.22×10^2	4.8×10^5
	20	-5.35×10^2	4.8×10^5
	40	-5.38×10^2	5.0×10^5
	75	-5.40×10^2	5.5×10^5
PBX-2	5	-4.69×10^2	4.6×10^3
	40	-4.80×10^2	4.8×10^3
	75	-4.85×10^2	5.1×10^3



a. 20 ℃ b. 75 ℃

Fig. 10 Calculated shock pressure profiles in the shock initiation of PBX-1 at different temperatures

Based on the ignition and growth modeling parameters calibrated by the experiments, it is possible to numerically simulate the shock initiation processes of samples which are impacted by various input pressures and obtain the "pop plot". The relative shock sensitivity of PBX-1 and PBX-2 at different initial temperatures is illustrated on the "pop plot" shown in Fig. 11. The "pop plot" represents a plot of run distance to detonation as a function of impact pressure in a log-log space. The closer the points are to the origin of the plot the more sensitive the explosive is to shock pressure. From Fig. 11 a clear progression from least sensitive at 5 ℃ to most sensitive at 75 ℃ for both of PBX-1 and PBX-2 is observed. In fact, for the same input pressure, the run distances to detonation of PBX-1 and PBX-2 at 75 ℃ are about 30% and 20% shorter than that of PBX-1 and PBX-2 at 5 ℃ respectively, this indicates that the effects of near-ambient temperature changes on the safety of the explosives cannot be ignored.

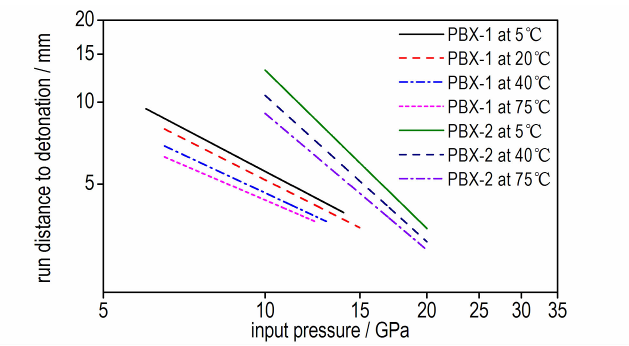


Fig. 11 Pop-plot for PBX-1 and PBX-2 at different initial temperatures

5 Conclusions

(1) As temperature changing from 5 ℃ to 75 ℃, the shock initiation pressure in both of the two PBXs grew more rapidly, the run distance to detonation became shorter and the reaction rate model constant G_1 increased gradually, these indicated that the two explosives became more sensitive to shock as near-ambient temperature increasing.

(2) The reasons for the samples at higher initial temperature being more sensitive to shock were: thermal expansion which led to lower density and the creation of more voids within the explosives and thus more hot spots to initiate reaction and faster growth of these hot spots into the surrounding particles and consequently made the explosives easier to be initiated.

(3) The effects of near-ambient temperature changes on safety of explosives could not be ignored.

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常温附近温度变化对炸药冲击起爆特征的影响

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摘 要: 为了研究常温附近温度变化对炸药冲击起爆特征的影响程度和规律,设计并建立了炸药局部加热和冷却装置,结合拉氏分析方法研究了 HMX/TATB 基复合高能炸药 PBX-1 和 TATB 基钝感高能炸药 PBX-2 在常温附近(5 ~75 ℃)的冲击起爆压力成长过程。基于实验结果,利用点火增长模型对两种炸药的冲击起爆过程进行了数值模拟。结果表明,随着温度升高(5 ~75 ℃),炸药的冲击起爆压力成长过程均逐渐变快,到爆轰距离变短,点火增长模型中的反应速率参数 G_1 变大,说明两种炸药随温度的升高对冲击变得更敏感,常温附近温度变化对炸药安全性的影响不能忽略。

关键词: 冲击起爆; 常温附近; 点火增长模型; 安全性
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