Research paper

Experimental researches on the micro-charged PBXN-5 detonation growth rules

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Abstract

In order to study the micro charge detonation growth rules, a method through experimental tests was used to measure the output pressure with different heights. The output pressure was accurately obtained by manganin piezo-resistance method to get the fitting curves and expressions of detonation characteristics about micro-charged PBXN-5 with two different charge diameters and densities. The results shows that under the same condition of the donor detonator charge, the output pressure with Φ 0.9 mm and 1.497 $g \cdot cm^{-3}$ charge charge had no apparent difference compared with the incident shock wave pressure, and detonation growth process was not obvious, while Φ 0.9 mm and 1.785 $g \cdot cm^{-3}$ charge an obvious detonation growth process indicated that density also has a significant impact on the detonation growth. There existed an obvious detonation growth process with Φ1.88 mm charge. Within the heights of 1 ~ 4 mm, the detonation grew significantly ; while more than 4 mm, the detonation growth trended towards sufficient stability.

Keywords : micro charge, detonation growth, manganin piezo-resistance method.

1. Introduction

In recent years, with the weapon system miniaturization, various types of pyrotechnics devices have taken up less space, meanwhile, the charge size has also been greatly hampered. According to GJB 862−90, the existing minimum detonating tube size is Φ 2.84 mm, and the future application of pyrotechnic devices in the MEMS system trends towards elaboration. Because of the critical dimension, diameter effect, confinement effect and other non-ideal detonation phenomena, the detonation under micro charge is extremely complex. For this reason, the explosive detonation under micro charge and micro channel, which has close relation with all kinds of micro and small pyrotechnic products, is currently the technological basis of weapons and ammunition under development.

Detonation physics[1] reveals that the detonation pressure and charge sizes are closely related, and, the detonation pressure is an important parameter that to evaluate the explosive detonation performance. The research of accurate detonation pressure measurement has great significance to the practical applications.

The study on detonation growth already has a long history. In 1969, Scott[2] measured the process of detonator detonation growth by high-speed photography. In 2012, Yan Nan et al. studied the detonation growth rules of micro lead azide charge[3]. Current researches on small explosives are mainly concentrated on charge diameter and constraint effects on detonation velocity and pressure[4),5)], whereas, for small size booster explosives, it is a new topic to use quantitative detonation pressure tests to study charge height's effect on the detonation growth. Therefore, the study of detonation growth characteristics under the condition of small and micro charge is of great significance.

PBXN-5, a plastic bonded explosive based on HMX, is a new insensitive booster explosive which has developed rapidly in recent years. In this paper, as the output power

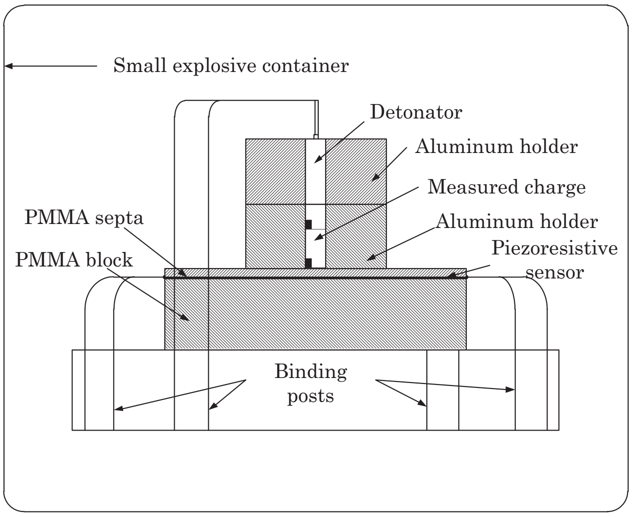

Figure 1 The schematic diagram of micro charge detonation pressure measurement system.

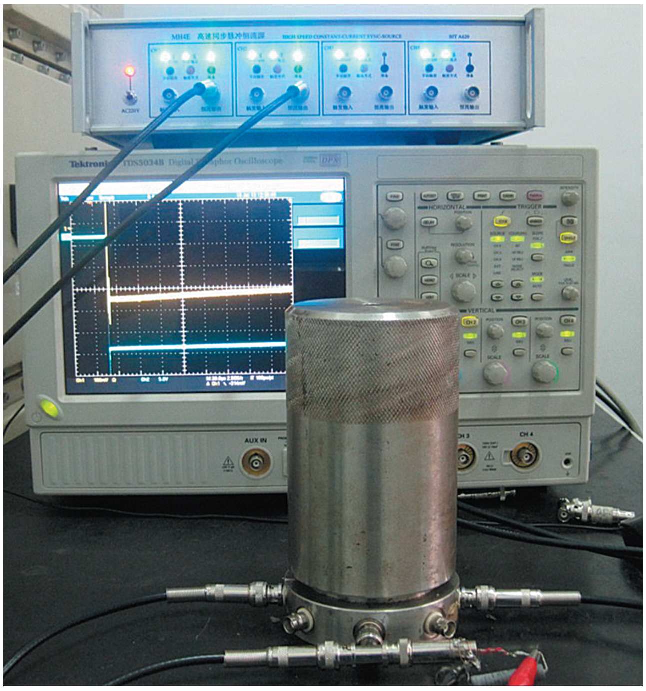

Figure 2 General arrangement of measure system.

of micro detonator was fixed and the charge heights and densities were changing, the output detonation pressure of micro-charged PBXN-5 was accurately measured by experimental researches via self-designed micro manganin piezoresistive sensors. The detonation growth characteristics of PBXN-5 were obtained and provided a valuable reference for the relevant researchers.

2. Experimental

2.1 Test system

In order to attain output pressure of micro-charged explosives with different charge heights, an output pressure test system was designed as Figure 1. In the present test, the electric detonators and micro-charged explosives were fixed with aluminum holder to reduce the lateral rarefaction wave effect as much as possible and to improve the quality of assembly positioning.

The basic test principles were as follows: after the micro electric detonator detonated the micro charge, the output shock pressure acted on the self-designed micro manganin piezoresistive sensor through 1 mm thick plexiglass protective septa. The resistance change of the sensor was recorded by the testing system. The waveform oscilloscope recorded the voltage variation process, and then measured the peak voltage U_{max} and voltage base U_0 through $\Delta R/R_0 = (U_{max} - U_0)/U_0$. These parameters were substituted to the pressure calibration formula of the sensor, and the output pressure peak can be obtained after these steps.

General arrangement of measure system was shown in Figure 2, which consisted of the following components: MH4E constant-current device with high-speed synchronous pulse, a small explosion container, DPO7104 digital storage oscilloscope.

H-type micro manganin piezoresistive sensor was chosen in this test shown in Figure 3. The sensitive area of the sensor was a rectangle with an area of about 0.04 mm^2, resistance of about 0.2 Ω and the total measured thickness of about 30~50 μm, which was coated by insulating films on both sides.

The calibration curve of H-type micro manganin piezoresistive sensor was given by:

$$\begin{cases} P = 53.22 \times \dfrac{\Delta U}{U} (0 \sim 5.907\,\mathrm{GPa}) \\ P = 1.978 + 35.28 \times \dfrac{\Delta U}{U} (\geq 5.907\,\mathrm{GPa}) \end{cases}$$

Where P is detonation peak wave pressure, in GPa; $\Delta U/U$ is change rate of voltage across the sensor.

Because there was 1 mm thick plexiglass protective septa at the top of the sensor, the pressure obtained from the sensor should be corrected according to the attenuation formula of shock wave in the PMMA[6]:

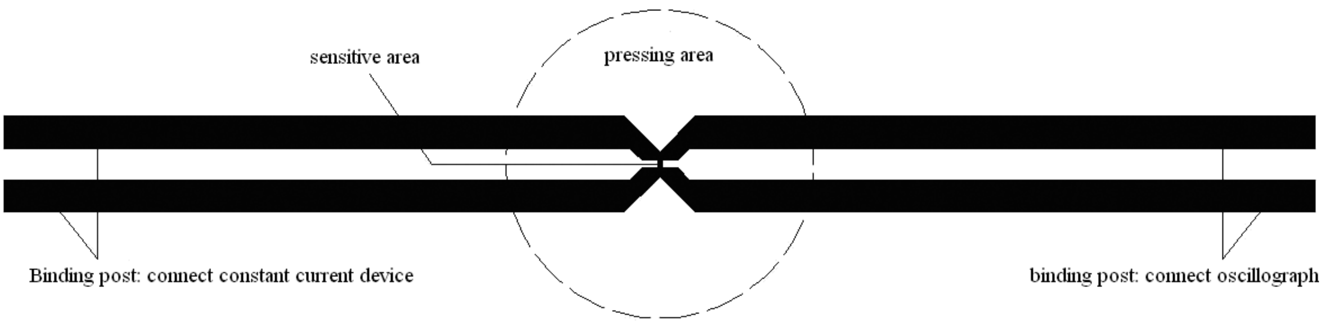

Figure 3 Structural sketch of micro manganin piezoresistive sensor.

Table 1 Experimental plans.

Charge diameter [mm]	Charge pressure [MPa]	Charge density [g·cm^{-3}]	Charge height [mm]	Donor charge size [mm]	Donor shock wave pressure [MPa]
0.9	65.8	1.497	0.6, 1.2, 1.5, 1.8, 2.4, 3.0	$\Phi 0.9 \times 3$	8.17
0.9	197.3	1.785	0.6, 1.2, 1.5, 1.8, 2.4, 3.0	$\Phi 0.9 \times 3$	8.17
1.88	62.09	1.645	1, 2, 3, 4, 5, 6	$\Phi 0.9 \times 3$	8.17
1.88	179.98	1.917	1, 2, 3, 4, 5, 6	$\Phi 0.9 \times 3$	8.17

$$\begin{cases} P = P_0 e^{-\alpha x} \\ \alpha = 0.0906 + 0.8615 e^{\frac{d}{2.1743}} \end{cases}$$

Where P_0 is the actual pressure, in GPa ; P is the pressure of the shock wave entering x mm into the PMMA, in GPa ; α is the attenuation coefficient of the shock wave in PMMA ; d is the diameter of charge, in mm.

2.2 Experimental program

For micro-charged explosives, the main factors that affect the output pressure are the charge type, charge diameter, charge density and charge height. When designing the program, with full consideration given to the application prospects of micro detonating tube, the experimental explosive type was fixed as PBXN-5 and the charge diameter was selected as Φ1.88 mm and Φ 0.9 mm to give full consideration to the application of the present and the future. Meanwhile, to get as many points and values as possible and avoid pressure values overlapping, six different charge heights were chosen with each charge diameter. The consistency of charge height was ensured by tube heights in the experiment. The minimum and maximum densities of detonating tube that could be applied were considered, and two kinds of charge densities were selected as comparison, then the detonation growth rules could be observed. The experimental program was shown in Table 1.

3. Results and analysis

At different densities, charge diameters and charge heights, the shock wave pressure was measured in the tests by using manganin piezoresistive sensors and Figure 4 shows the typical test signal. When the constant-current device kept supplying the detonator and sensor with power simultaneously for approximately 133 μs, the sensor was affected by the shock wave due to the detonation of micro charge, then an abrupt signal of voltage quickly detected by the sensor is close to a straight line, and this is known as the piezoresistive signal. According to the value of ΔU and U_0 and the calibration equation of the sensor, the shock wave pressure was obtained. It should be noted that the measured pressure needs to be corrected because the shock wave can be attenuated through a 1 mm plexiglass film. The obtained pressure is the maximum pressure at the center of the wave front of micro charge. Table 2 shows the measured PBXN-5 detonation pressure with different densities, charge diameters and heights.

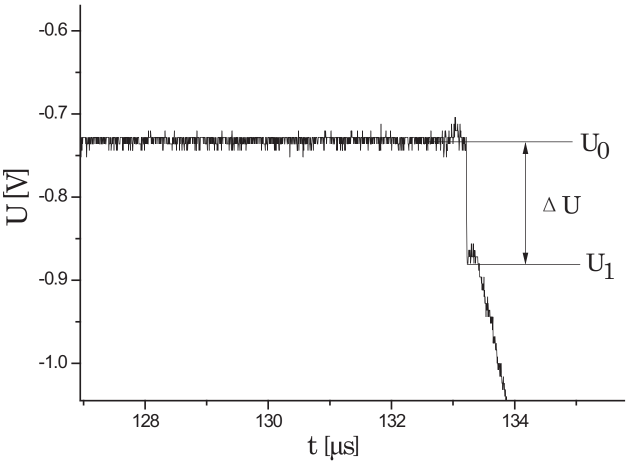

Figure 4 Typical testing signal of micro manganin piezoresistive sensor.

Because the lateral rarefaction wave in the detonation propagation process of micro-charged PBXN-5 explosive cannot be ignored, the micro charge detonation presents typical features of non-ideal detonation. For a particular diameter charge, there exists a characteristic shock wave pressure at a certain charge density. By analyzing the data characteristics in Table 2, the relationships between output pressure and charge heights with different densities and charge diameters were shown in Figure 5, and it can be seen that :

(1) There exist remarkable differences in the relationships of output pressure and charge heights with different charge diameters and densities. It appears no significant differences between the output pressure and the incident shock wave pressure with Φ 0.9 mm and 1.497 g·cm^{-3} charge, and detonation growth process is not quite obvious. Hence, the linear fitting method should be used for analysis and the average value of shock wave pressure with different charge heights is considered as the stable shock wave pressure. The detonation progress with Φ1.88 mm or Φ 0.9 mm and 1.785 g·cm^{-3} charges involves the steps of initial growth, transition and stabilization phase, thus an exponential fitting method is adapted to analyze detonation growth process. The fitting curves are shown in Figure 5 and the fitting formulas are as follows :

$P = 19.827 - 17.860 \exp(-h/1.396)$,

charge diameter is Φ1.88 mm and charge density is 1.917 g·cm^{-3} and the application range is 1 mm ≥ h ≥ 6 mm.

$P = 19.444 - 14.808 \exp(-h/2.154)$,

charge diameter is Φ1.88 mm and charge density is 1.645 g·cm^{-3} and the application range is 1 mm ≥ h ≥ 6 mm..

Table 2 Measured detonation pressure of different heights of PBXN−5 with micro charge.

ID	Charge diameter [mm]	Charge density [g·cm⁻³]	Height [mm]	Shock wave pressure on sensor surface P[GPa]	Shock wave pressure after correction P_0[GPa]	Total number
1	0.9	1.497	0.62	4.64	8.97	10
2			1.23	4.62	8.94	11
3			1.55	4.61	8.93	9
4			1.85	4.63	8.96	11
5			2.42	4.81	9.31	9
6			2.95	4.75	9.19	9
7	0.9	1.785	0.62	4.43	8.57	9
8			1.22	4.66	9.02	9
9			1.52	4.78	9.24	8
10			1.83	4.96	9.59	7
11			2.43	5.12	9.91	7
12			2.95	5.28	10.22	8
13	1.88	1.645	1.09	6.73	10.59	8
14			2.22	8.81	13.86	10
15			2.95	10.08	15.86	9
16			3.94	10.95	17.23	8
17			4.94	11.38	17.91	9
18			6.01	11.73	18.46	9
19	1.88	1.917	1.11	7.44	11.71	8
20			2.31	10.57	16.63	10
21			2.97	11.28	17.75	10
22			3.84	11.61	18.27	10
23			4.96	12.24	19.26	9
24			5.96	12.60	19.83	9

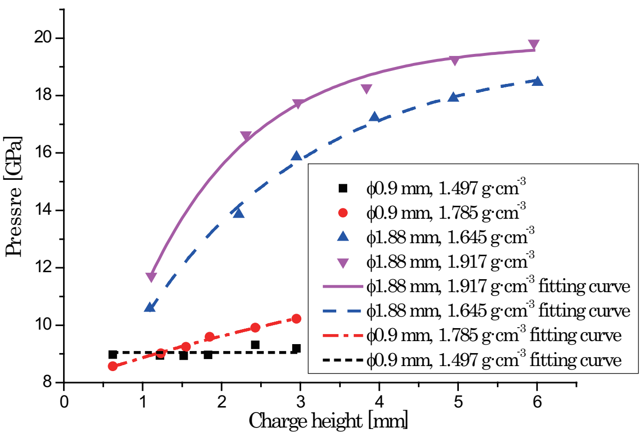

Figure 5 Relation between detonation pressure and charge heights of PBXN-5 with micro charge.

$P = 14.233 - 6.237\exp(-h/6.640)$,

charge diameter is Φ 0.9 mm and charge density is 1.785 g·cm^{-3} and the application range is 0.6 mm $\geq h \geq$ 3.0 mm.

$P = 9.05$,

charge diameter is Φ 0.9 mm and charge density is 1.497 g·cm^{-3} and the application range is 0.6 mm $\geq h \geq$ 3.0 mm.

(2) The detonation processes with two charge heights have the same initial shock wave pressure of 8.17 GPa, namely, the output pressure of the micro detonator. The shock wave pressure with Φ 0.9 mm and 1.497 g·cm^{-3} charge has no distinct detonation growth stage. This phenomenon can be explained by that the donor shock wave pressure and the characteristic shock wave pressure of the micro charge are very close, and the detonation transfers continuously between the donor and accepter charge. The micro charge reaches stable detonation at its interface with the donor charge, so there appears no shock wave pressure growth. While Φ1.8 mm charge has greater characteristic shock wave pressure, after being detonated by the donor charge, it still needs to go through the detonation growth process to reach steady state. For instance, with the charge height range of 1 ~ 3 mm, the shock wave pressure increases to 15.86 GPa at the lower density and 17.75 GPa at the higher density, thus it can be seen that the shock wave pressure increases significantly.

(3) The detonation growth rate declines with the decrease of the diameter. There exist differences in change trends of charge output pressure versus charge height with Φ 0.9 mm and two different charge densities. This is because higher loading densities make higher shock pressure and greater detonation growth distances. While the output pressure of Φ1.8 mm charge has distinct variances with different densities, the pressure wave keeps increasing with the density. Within the range of 1 ~ 6 mm, the detonation pressure at the higher density is greater than that at the lower density, with a maximum deviation of 16.7 %.

(4) When the detonation grows to a stable level, characteristic shock wave pressure or the charge heights are significantly different with two charge diameters. Φ 0.9 mm and 1.497 g·cm^{-3} charge reaches stable detonation at the interface between the micro charge with the micro detonator, and the characteristic shock wave pressure is 9.05 GPa. For Φ 0.9 mm and 1.785 g·cm^{-3} charge, when the charge height is 1 ~ 3 mm, the detonation grows significantly, and when around 3 mm, the shock wave pressure stabilizes gradually, so the distance of detonation growth can be considered as 3 mm. The stable detonation pressure with 1.785 g·cm^{-3} charge is estimated as 10.22 GPa. Similarly, the distance of detonation growth with Φ 1.88 mm charge can be considered as 4 mm, and the stable detonation pressure at the lower density is 17.23 GPa and increases by 110.9% compared with the input pressure value, while at the higher density is 18.27 GPa and increases by 123.6%.

This phenomenon can be interpreted as the typical diameter effect. The lateral expansion leads to the decrease of the energy density in reaction zone and the wave front strength, and reduction of the inspired chemical reaction rate which decreases the detonation wave propagation speed. This in turn broadens the reaction zone and weakens the detonation strength. Such a detrimental cycle causes that when the energy released in reaction zone can compensate the energy loss, the detonation wave transmits with the detonation velocity and detonation pressure corresponding to a certain charge diameter.

It can be seen from Figure 5 that the charge diameter has a significant impact on the detonation pressure, and there have been detonation velocity tests with different charge diameters in the previous work[7]. From the fitting curve of test results we can get the detonation velocity of 6580 m·s^{-1} and 7317 m·s^{-1} with ϕ 0.9 mm and ϕ 1.88 mm respectively. As mentioned above, due to the existence of non-ideal detonation, detonation velocity versus detonation pressure with micro charge cannot be described by certain relations.

For the researches concerning detonation growth rules, most previous work concentrated on the large-charged explosives, but rarely on micro-charged explosives detonation trains, and among these researches, there are two famous examples. One is the study by Scott on the detonation growth process in the detonator[2]. High speed scanning cameras and electric probes were used in the experiments to discover that high-speed detonation of lead azide occurred with a length of 1.52 mm or over and a diameter of 3.73 mm, then trended towards stability ; The other is the study on detonation growth rules in Sandia National Laboratories from the year of 2005 to 2007 to promote the development and the miniaturization of initiating explosive devices in the future, and micro-charged detonation growth rules were achieved by using high-speed schlieren photography[8)-11)]. However, both the examples are based on image analysis and qualitative observation.

In contract, in this paper, by using the self-designed manganin piezoresistive sensor and experimental apparatus, the detonation pressure measurement of the micro-charged explosive was implemented, with the minimum charge quantity of 1 mg. In this work, the micro-charged PBXN-5 explosive detonation pressure was directly measured under different conditions, and the detonation growth rules was quantitatively described, which was of great significance to the related researches on detonation process.

4. Conclusions

In this paper, the detonation growth rules of micro-charged PBXN-5 were obtained in the study of experimental researches and manganin piezoresistive sensors were used in the experiments, the main conclusions are as follows :

(1) Under the same condition of the donor detonator charge, the output pressure with Φ 0.9 mm and 1.497 g·cm^{-3} charge has no apparent differences compared with the incident shock wave pressure, and detonation growth process is not obvious, while Φ 0.9 mm and 1.785 g·cm^{-3} charge an obvious detonation growth process indicates that the density also has a significant impact on the detonation growth.

(2) Stable detonation with Φ 0.9 mm and 1.497 g·cm^{-3} charge appears at the interface between the micro charge with the micro detonator, and the characteristic shock wave pressure is 9.05 GPa. While for Φ 0.9 mm and 1.785 g·cm^{-3} charge, the distance of detonation growth is 3 mm and the characteristic detonation pressures is 10.22 GPa.

(3) Φ1.88 mm charge has an obvious detonation growth process. The distance of detonation growth is 4 mm. The characteristic detonation pressures respectively are 17.23 GPa and 18.27 GPa at 1.645 g·cm^{-3} and 1.917 g·cm^{-3}.

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