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Experimental studies on a horn-shaped booster pellet

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All insensitive munitions contain explosive trains which need to meet insensitive munitions criteria but reliably initiate the main charge explosives. The traditional cylindrical booster pellets have insufficient energy output for reliably initiating the insensitive main charge explosives. To ensure that the requirement can be achieved, a horn-shaped booster pellet having high initiation capacity was designed and experimentally studied. The results show that the horn-shaped booster pellet has higher initiation capacity than the cylindrical booster pellet for the same mass and density of explosive. The convergence pressure of the horn-shaped booster pellet is 34 GPa, which is higher than the value of 27 GPa for the cylindrical booster pellet.

Keywords: booster pellet, insensitive main charge, pressure, initiation capacity.

INTRODUCTION

The first demonstration of the Munroe effect for high explosives was achieved by Munroe C. E. in 1885 [1]. In one of his experiments, Munroe observed that when a cavity was formed in a cylinder of explosive, opposite the point of initiation, the depth of the crater produced in the steel target was deeper compared with the cylindrical explosive without cavity. The increase in penetration resulted from the focusing of the detonation products by the hollow cavity. The history of shaped charges was discussed in reference [2].

Now, the shaped charge effect is widely applied in the following fields: the common term in military terminology for shaped charge warhead is high explosive anti-tank (HEAT). HEAT warheads are frequently used in anti-tank guided missiles, unguided rockets, rifle grenades, and various other weapons. In non-military applications, shaped charges are used in the explosive demolition of buildings and structures, in particular for cutting through metal piles, columns and beams [3]. Shaped charges are used most extensively in the petroleum and natural gas industries, in particular in the completion of oil and gas wells, in which they are detonated to perforate the metal casing of the well at intervals to admit the influx of oil and gas [4]. Shaped charge technique is also regarded aimed at the formation of hypervelocity fragments for the investigation of space debris effects on shielding screens [5, 6]. Smirnov [7] considered the problem of non-stationary formation of a cumulative jet in a medium that offers resistance to the motion of the jet and obtained an analytical solution of the non-stationary problem. However, the number of studies using the shaped charge effect to initiate insensitive explosives is limited.

The insensitive main charge explosives are assuming a key role in the development of modern weapons. The exploitation of the insensitive munitions technology resulted in improved survivability from accidents, enemy actions, weapon systems and their associated platforms [8]. The munitions contain a number of explosive trains to provide reliable initiation and detonation transfer. The main charge explosives filled in the weapons are becoming increasingly insensitive to hazard stimuli. The traditional method of increasing the energy output for reliably initiating the insensitive main charge explosives is to increase the size and amount of the booster explosives [9]. This approach resulted in the explosive train becoming a significant factor in weapons vulnerability.

The developmental efforts in booster explosives have therefore been aimed at highly effective booster charge structures that reliably initiate insensitive main charge explosives in small size and quantity.

Dallman [10] investigated the initiation capacity of a hemispherical booster pellet and reported that its output is powerful even when it is small in size. Spahn [11, 12] conducted studies on an embedded can booster and also a booster explosive ring. The results showed that the initiation capacities of the embedded can booster and booster explosive ring are more powerful than the initiation capacity of a cylindrical booster pellet. In a recent work of the authors [13], the initiation capacities of the ring and conical ring booster pellets were studied. The results showed that the initiation capacities of the ring and conical ring booster pellets are higher than those of

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the cylindrical pellets. The energy output of the conical ring booster pellet was found to be higher than that of the ring booster pellet.

In this paper, a booster pellet with a horn-shaped cavity was experimentally studied. The initiation capacities of horn-shaped and cylindrical booster pellets were compared.

DESIGN THEORY

In order to produce a powerful convergence shock wave, the products moving to the focus from different points of the explosive surface should be simultaneously converged. The problem in two dimensions was studied and an "energy-convergence" curvilinear equation was deduced. The diagram of the energy-convergence surface is shown in Fig. 1.

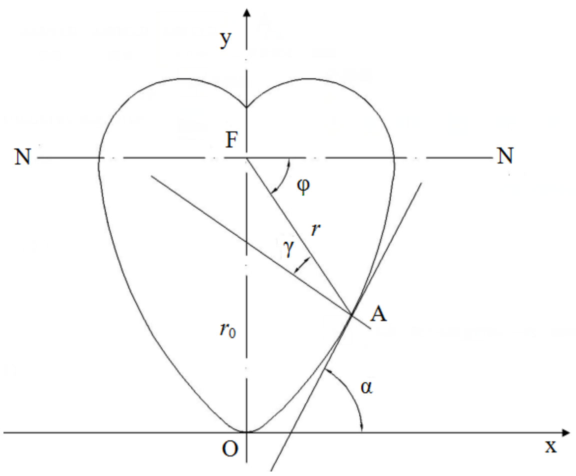

Fig. 1. Diagram of the energy-convergence surface

Origin of the coordinates is set on the focus of this curve. Suppose explosion starts from the point O. According to the Fermi principle, it can be got that

$$\frac{\overset{\frown}{\mathrm{OA}}}{D}+\frac{\mathrm{AF}}{\overline{u}}=\frac{\mathrm{OF}}{\overline{u}}=\mathrm{const} \tag{1}$$

where point A is any point along the charge surface, point F is the convergence focus of explosion products, arc OA is the propagation distance of detonation wave, lines AF and OF are the propagation distances of explosion products. D is the detonation velocity, $\overline{\mu}$ is the velocity of explosion products. Then, the length expression of arc OA could be gained,

$$\overset{\frown}{\mathrm{OA}}=\int_{\frac{\pi}{2}}^{\varphi}\sqrt{r^2+(\frac{dr}{d\varphi})^2}\,d\varphi=(\mathrm{OF}-\mathrm{AF})\frac{D}{\overline{u}}=\frac{D}{\overline{u}}(r_0-r) \tag{2}$$

where r is the length of line AF, r_0 is the length of line OF, φ is the angle between line FN and line FA. Through φ differential to Equation (2), it gets

$$\frac{dr}{r}=-\frac{d\phi}{\sqrt{\frac{D^2}{\overline{u}^2}-1}} \tag{3}$$

solve it and then,

$$r=r_0\mathrm{e}^{\frac{\varphi+\frac{\pi}{2}}{\sqrt{\frac{D^2}{\overline{u}^2}-1}}} \tag{4}$$

This is the logarithmic spiral equation.

After the surface of revolution (rotation axis is line OF) is formed, the energy-convergence surface that forms the convergence shock wave could be calculated. As we know, the logarithmic spiral has the following property: the angle between the tangent line of any point A and the radius vector is a constant. It can be seen clearly from Fig. 1 that this angle is $90^\circ-\gamma$ (γ is the angle between the normal line of any point A and the radius vector), and $90^\circ-\gamma=180^\circ-(\alpha+\phi)$ (α is the inclination angle of the tangent line).

Therefore,

$$\gamma=\alpha-90^\circ+\phi \tag{5}$$

Since

$$\tan(90^\circ-\alpha)=\cot\alpha=\frac{\frac{r'}{r}-\tan\phi}{\frac{r'}{r}\tan\phi+1}= \tag{6}$$

$$\tan[\arctan\frac{r'}{r}-\phi]=\tan[-(\phi+\gamma)]$$

So,

$$\arctan\frac{r'}{r}=-\gamma \tag{7}$$

$$\frac{r'}{r}=-\tan\gamma \tag{8}$$

However, we have known that,

$$\frac{r'}{r}=-\frac{1}{\sqrt{\frac{D^2}{\overline{u}^2}-1}} \tag{9}$$

Therefore,

$$\tan\gamma = \frac{1}{\sqrt{\frac{D^2}{\overline{u}^2} - 1}} \tag{10}$$

$$\sin\gamma = \frac{\overline{u}}{D} \tag{11}$$

So, the logarithmic spiral is the sole curve during focusing of explosion products, the logarithmic spiral not only has the property of Fermi principle, but also could guide the explosion products from every surface element to the focus at the same parameters and same angle.

The volume charge is formed by rotation of the logarithmic spiral centered as line OF. It could produce convergence shock wave of explosion products. If the volume charge is large enough in size, it could generate pressure of millions of atmospheric pressure at the focus. The average initial pressure of the explosion products is equal to 100000 atmospheric pressures.

The surface formed by rotation of the logarithmic spiral is the “energy-convergence” surface of the charge. Cut the charging part (e.g. along the plane N-N) that is formed by rotation of a logarithmic spiral, and the actual energy-convergence charge which could generate high pressure could be acquired.

According to that, the horn-shaped booster pellet was designed and it is shown in Fig. 2.

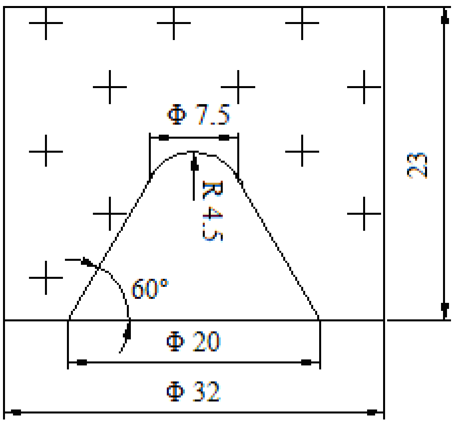

Fig. 2. Structure and size of the horn-shaped booster pellet

EXPERIMENTS

Experimental method

Four different methods were selected to comprehensively study the initiation capacity of the horn-shaped booster pellet [14, 15].

(1) Main charge detonation distance method. The main charge is initiated by the booster pellet. The detonation distance of the main charge represents the initiation capacity of the booster pellet. The detonation distance of the main charge is affected by the initiation energy of the booster pellet. The more powerful the initiation energy is, the longer the detonation distance propagates.

(2) Main charge axial-steel-dent method. In this method, the main charge in contact with the steel witness plate is directly initiated by the booster pellet. The depth of the dent represents the initiation capacity of the booster pellet.

(3) Booster pellet axial-steel-dent method. The booster pellet is in direct contact with the steel witness plate. Initiated by the detonator, the booster pellet detonates and produces a steel dent. The depth of the dent represents the initiation capacity.

(4) Pressure test method. In the pressure test method, low-resistance manganin piezoresistors sensor was used for accurate measurement of the convergence pressure [16, 17].

The convergence pressure could be calculated by using the following relationship:

$$p = 0.9447 + 35.5887 \times (\frac{\Delta R}{R}) + 6.986 \times (\frac{\Delta R}{R})^2 \tag{12}$$

where, R is the resistance of the manganin piezoresistors sensor, ΔR is the variation of resistance, p is the convergence pressure.

In the experiment, a constant current source was used to measure $\Delta U/U$ by an oscillograph. $\Delta R/R$ was obtained from the following relationship:

$$\frac{\Delta R}{R} = \frac{\Delta RI}{RI} = \frac{\Delta U}{U} \tag{13}$$

where, U is the voltage, ΔU is the variation of voltage, I is the electric current.

Experimental conditions

The plastic-bonded booster explosive PBXN-5 was selected for the experiments. The density of the compacted booster pellet was 1.68 g/cm^3. The density and diameter of the cylindrical pellet were 1.68 g/cm^3 and 29.58 mm, respectively.

Nitroguanidine-based composite explosive was chosen as the main charge. The nitroguanidine-based composite explosive contains nitroguanidine (NQ), polytetrafluoroethylene (PTFE) and graphite (G).

The steel witness plate was an ordinary carbon steel of size Φ100×50 mm.

Experimental devices

The experimental device of the main charge axial-steel-dent method and the main charge detonation distance method is shown in Fig. 3. The booster pellet axial-steel-dent method is similar to

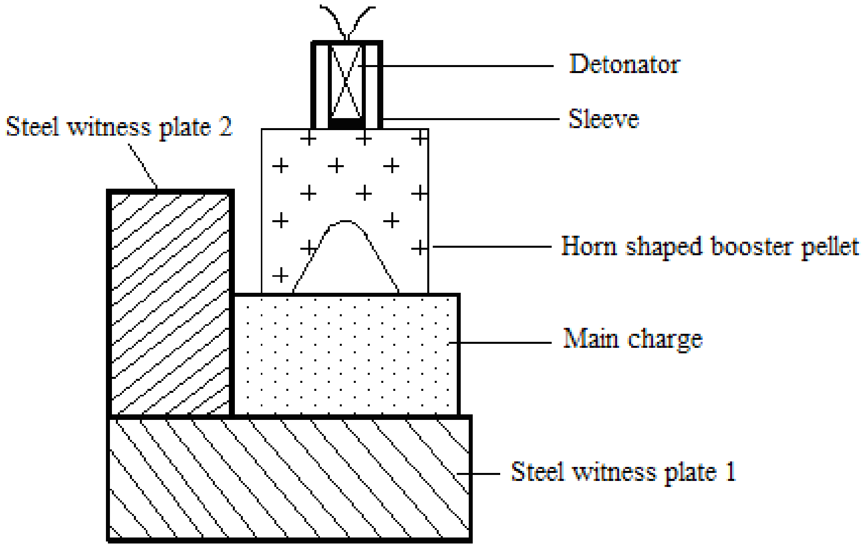

Fig. 3. Experimental device of the main charge axial-steel-dent method and the main charge detonation distance method

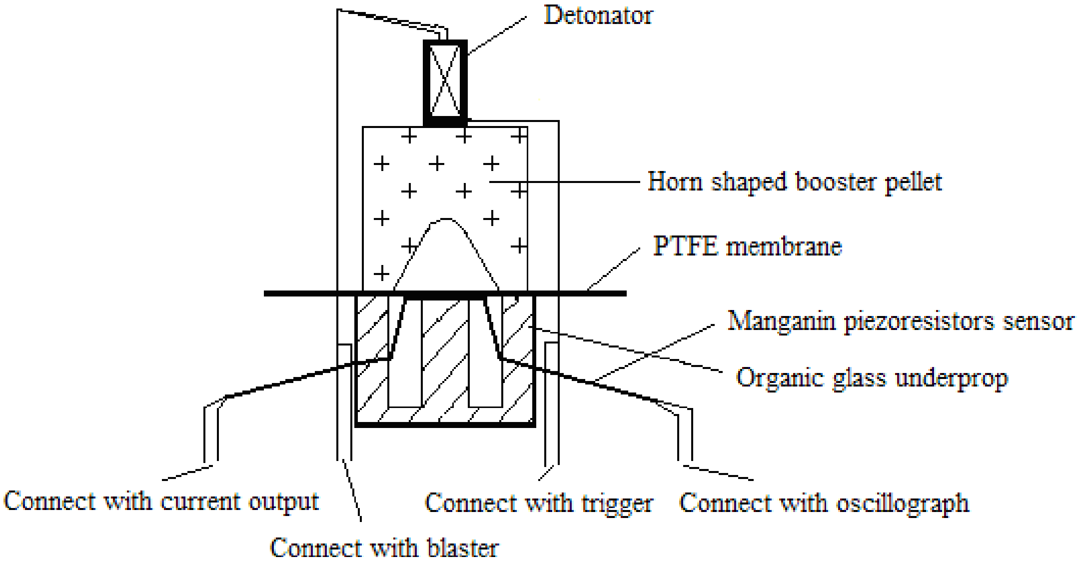

Fig. 4. Installation diagrammatic illustration of the pressure test method

the main charge axial-steel-dent method except that it excluded the main charge and the steel witness plate 2. The testing instrument used for measuring the convergence pressure is illustrated in Fig. 4.

EXPERIMENTAL RESULTS AND DISCUSSION

Comparison of initiation capacities of horn-shaped and cylindrical booster pellets

The initiation capacities of the horn-shaped and cylindrical booster pellets were measured using the main charge detonation distance method. The main charge explosive was an NQ-based composite explosive. The components of the main charge were in the following proportions: NQ/PTFE/G=46/53/1. The density, diameter and height of the NQ-based composite explosive were 1.17 g/cm^3, 70.0 and 80.0 mm, respectively. The results obtained from the experiments are presented in Table 1.

The results in Table 1 show that when the main charges were initiated by the horn-shaped booster pellet and the cylindrical pellet at the same density of explosive, the average detonation distance of the main charge initiated by the cylindrical booster pellet is 55 mm. However, the one initiated by the horn shape booster pellet is 75 mm. Therefore, the horn shaped booster pellet has more initiation capacity than the cylindrical booster pellet for the same mass and density of explosive.

The data of the present work are the results of five parallel experiments. The detonation distances of the main charge initiated by the cylindrical booster pellets are 54.5, 54.8, 55.2, 56.2, 56.4 mm, respectively, the variance value of the data is 0.57. The detonation distances of the main charge

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Table 1. Results of the initiation capacities of booster pellets for the detonation distance method

Booster pellet		Main charge		
Shape	Mass (g)	Height (mm)	Average Detonation Distance (mm)	Time of Experiment
Horn-shaped booster pellet	19.6	80±0.2	75.04	5
Cylindrical booster pellet	19.6	80±0.2	55.42	5

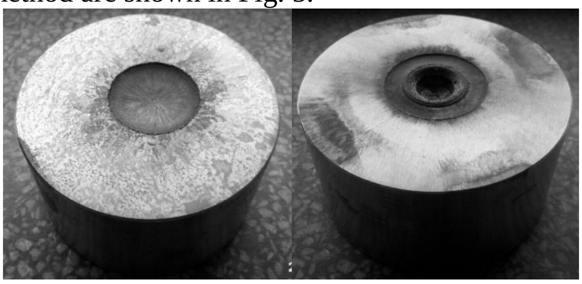
Table 2. Results of the initiation capacities of booster pellets for the axial-steel-dent method and pressure test method

Shape	Mass, (g)	Dent depth of method (2), (mm)	Dent depth of method (3), (mm)	Convergence pressure, (GPa)
Cylindrical	19.7	1.20	2.65	27
Cylindrical	22.4	1.46	3.02	
Cylindrical	26.7	1.72	3.44	
Cylindrical	33.1	1.90	3.86	
Horn-shaped	25.3	2.16	11.62	34

initiated by the horn shape booster pellets are 73.8, 74.1, 75.2, 75.3, 76.8 mm, respectively, the variance value of the data is 1.12. The variance values were small, therefore, it can be reasonably considered that the results are true and considerably credible.

Additional studies on the initiation capacity of horn-shaped booster pellet

Experiments using the main charge axial-steel-dent, booster pellet axial-steel-dent, and pressure test method were also conducted. The components of the main charge were in the following proportions: NQ/PTFE/G=70/29/1. The density, diameter and height of NQ-based composite explosive were 1.20 g/cm^3, 42.6 and 40 mm, respectively. The results are shown in Table 2. The pictures of the steel witness plates employed in the booster pellet axial-steel-dent method are shown in Fig. 5.



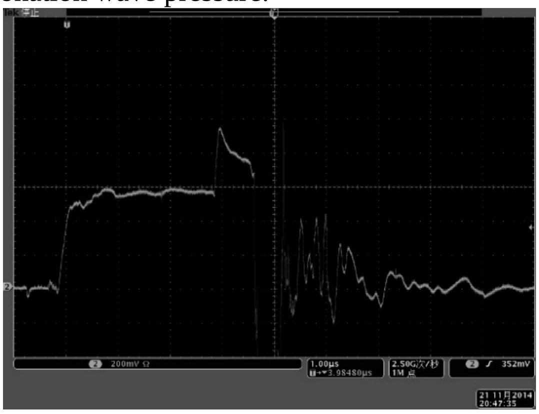
(a) depth=3.86 mm (b) depth=11.42 mm

Fig. 5. Steel witness plates for the booster pellet axial-steel-dent method

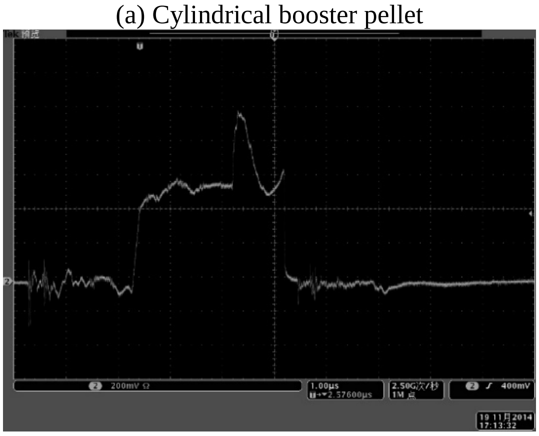
The pressure waveforms of the cylindrical and horn shaped booster pellets are shown in Figs. 6 (a) and (b), respectively.

The steel dent depth of the horn-shaped booster pellet is higher than that of the cylindrical booster pellet for both main charge and booster axial-steel-dent methods. It can be seen that the convergence pressure of the new booster pellet is 34 GPa, which is higher than the value of 27 GPa for the cylindrical booster pellet. The results from the three methods are in good agreement.

From Fig. 5 (b) it can be seen that the hole at the center of the steel witness plate is deep and the ring around the hole is shallow. The hole at the center is produced by the convergence pressure. The ring dent is created by the detonation wave pressure. It is also seen that the convergence pressure is higher than the detonation wave pressure.



(a) Cylindrical booster pellet



(b) Horn-shaped booster pellet

Fig. 6. Pressure waveform of the cylindrical and horn-shaped booster pellets

The dent depth *h* is expressed as [18, 19]:

$$h = \mathrm{M}\frac{(p_0 - \sigma_s)^2}{p_0\sqrt{p_0\sigma_s}} r_e \tag{14}$$

where, h is the dent depth, M is a constant determined by the explosive and metal material, p_0 is the pressure of the shock wave, σ_s is the dynamic elastic limit of the metal material, r_e is the explosive radius. So, the higher the shock wave pressure is, the deeper becomes the dent depth. That is to say that the horn-shaped booster pellet has more powerful energy output than the cylindrical booster pellet.

Factors influencing the experimental results

There are two main factors affecting the experimental results.

(1) Effect of PTFE powder content. The main charge explosive contains PTFE powder as the inert material. But the PTFE powder is difficult to be press molded. The more PTFE powder is added, the looser is the main charge. So, the densities of the main charge explosives are variable. The experimental results are not in agreement with each other, but the difference is small.

(2) Effect of the manganin piezoresistors. When the horn-shaped booster pellet is initiated, the detonation wave propagates downward in the form of a spherical wave. When the detonation wave reaches the energy cavity surface, the detonation wave attenuates into the shock wave. The shock wave begins to converge towards the energy cavity center, and the output pressure of the bottom center area of the horn-shaped booster pellet is the largest. However, the test point of the manganin piezoresistors sensor is very small, the size of the sensitive area is 0.5×0.5 mm. It is difficult to align the test point of the manganin piezoresistors sensor with the bottom center point of the horn-shaped booster pellet. Therefore, the data of the output pressure are not in agreement with each other, and the maximum one was chosen.

CONCLUSIONS

The initiation capacity of the horn-shaped booster pellet was studied experimentally. Following are the conclusions.

The initiation capacity of the horn-shaped booster pellet is higher than that of the cylindrical booster pellet for the same mass and density of explosive.

The output pressure of the horn shaped booster pellet was studied experimentally. The valve is much higher than that of the cylindrical booster pellet for the same density of explosive.

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ЕКСПЕРИМЕНТАЛНО ИЗСЛЕДВАНЕ НА РОГО-ОБРАЗНИ ВЗРИВНИ КАПСУЛИ

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(Резюме)

Всички муниции съдържат детонатори, които трябва да отговарят на определени критерии, но най-вече да инициират взривяването на основния експлозив. Традиционните цилиндрични взриватели нямат достатъчно енергия за надеждното взривяване на основния експлозив. За повишаването на тази надеждност, се предлагат нови рого-образни взриватели, проектирани и изпитани експериментално. Резултатите показват, че новите взриватели имат по-голям инициращ капацитет от цилиндричните при същата маса и плътност на експлозива. Конвергентното налягане на роговите капсули е 34 GPa, по-високо от налягането при цилиндричните капсули - higher than the value of 27 GPa.