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Citation for published version (APA):

Xing, B. Y., Liu, R. Z., Guo, R., Chen, L., Zhou, H., Yang, Y. L., & Liu, L. (2017). Influence of the embedded structure on the EFP formation of compact terminal sensitive projectile. *Defence Technology*, 13(4), 310-315. <https://doi.org/10.1016/j.dt.2017.05.006>

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DOI:
[10.1016/j.dt.2017.05.006](https://doi.org/10.1016/j.dt.2017.05.006)

Document status and date:
Published: 01/08/2017

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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Influence of the embedded structure on the EFP formation of compact terminal sensitive projectile

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ARTICLE INFO

Article history:

Received 16 January 2017

Received in revised form

17 April 2017

Accepted 17 May 2017

Available online 20 May 2017

Keywords:

Terminal sensitive projectile

Embedded structure

Detonation wave

EFP formation

ABSTRACT

To improve the damage efficiency of compact terminal sensitive projectile with EFP warhead, it is vital to understand how the embedded structure (ES) affects the EFP forming performance. In this paper, the corresponding numerical investigation is focused on, in which the fluid-structure interaction (FSI) method and the experimental verification are used. Based on the obtained quantitative relations between the forming performance and α (the ratio of height to maximum radius of ES), an optimal design is further provided. The results indicate that: when the embedded structural length and width range 0.1–0.3D and 0.1–0.2D (D: diameter of EFP warhead) at a fixed volume, respectively, EFP forming velocity nearly keeps as a constant, 1760 m/s; the height of ES has a dramatic effect on the propagating range of detonation wave, resulting in significant influence on the aerodynamic shape and length-to-diameter ratio of EFP; under the given constraints, the EFP length-diameter ratio can reach the optimal value 2.76, when the height of ES is 0.22D.

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1. Introduction

The wave shaper is widely used in the explosively formed penetrator (EFP) warhead as an adjuster of detonation wave propagation. In detail, it makes the liner concentrate to the axial orientation and EFP form more easily [1,2] so as to achieve a penetrator with larger length-to-diameter ratio and compacted shape.

However, in the terminal sensitive projectile, the millimeter-wave and infrared sensors are often used as ES directly for improving compactness [3,4]. The ES has the same effect on the propagation of detonation wave as the wave shaper does, but their size difference is significant. The ES usually has a relatively smaller diameter and larger axial thickness. In addition, their positions in the EFP warhead are different, where the ES is close to the geometric center of EFP warhead, while the wave shaper usually approaches to the back of EFP warhead [5]. In most cases, the ES decreases more charge space and affects its geometry significantly. As a result, the global forming performance of EFP warhead is weakened in some degree. For governing these negative influences,

it is necessary to understand how the ES influences the formation and the optimal embedded structural configuration is expected.

A lot of theoretical and simulation work has been done. Theoretical calculation and numerical simulation were used to study the influences of wave shaper and liner on EFP, and the relationship between the wave shaper and the liner configuration was studied to present a well-formed EFP matching relationship [6]. Li [7] pointed out that the ES can influence the shape of detonation wave. Zhang et al. [8] pointed out that the ES would enhance the crushing effect on the liner. Nurick et al. [9] pointed out that the change in explosive shape influenced the shape and depth of the shock front profile impinging upon the surfaces of the plates subjected to explosion loading via the detonation of plastic explosives.

At present, various methods can be used to investigate the EFP formation and the effect of the wave shaper on the propagation of detonation wave. But there has been little research on the effect of ES in the EFP warhead of compact terminal sensitive projectile on the detonation wave propagation and the EFP formation. AUTODYN-2D is adopted to consider the fluid–solid coupling problem [10,11]. The present paper uses AUTODYN™ to consider the fluid–solid coupling problem as well as analyze how the ES affects the propagation of detonation wave and the formation of EFP.

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Peer review under responsibility of China Ordnance Society

2. Numerical model

2.1. Material model

A material model of air was derived from the material library in AUTODYN™ [12].

The material of liner is copper. The relation between the velocities of shock wave D and material point u can be approximated by Ref. [7]

$$D = C_1 + S_1 u \quad (1)$$

where C_1 is the adiabatic velocity of sound in the material; and S_1 is a coefficient, the values of each parameter are given in Table 1 [7]

The material constitutive relation for the copper is described by the Johnson-Cook equation [7].

$$\sigma = (A + B\epsilon^n)(1 + C \ln \dot{\epsilon}) \left(1 - \left|\frac{T - T_r}{T_m - T_r}\right|^m\right) \quad (2)$$

where A , B , C , n and m are the parameters of material; ϵ is the plastic strain; $\dot{\epsilon}$ is the rate of plastic strain; T_m is the reference temperature; and T_r is the melting temperature of copper.

The material of a waveguide is aluminum. The main parameters of aluminum are shown in Table 2 [13].

The material of a shell is 45# steel. The main parameters of 45# steel are shown in Table 3 [7].

The material of an explosive is 8701. The equation of state (EOS) of explosive is chosen as JWL, the EOS is as follows [7]

$$P = A \left| 1 - \frac{\omega}{R_1 V} \right| e^{-R_1 V} + B \left| 1 - \frac{\omega}{R_2 V} \right| e^{-R_2 V} + \frac{\omega E_0}{V} \quad (3)$$

where P is the shock wave pressure; V is the volume ratio between detonation product and initial explosive; A , B , R_1 , R_2 and ω are the parameters of material; E_0 is the specific internal energy of 8701. The main parameters of 8701 are shown in Table 4 [7].

The material's name of ES is POLY-CARB. The main parameters of POLY-CARB are shown in Table 5 [7].

The material and EOS of each part of EFP warhead are shown in Table 6.

2.2. Calculation model

The finite element model is shown in Fig. 1, in which a detonation point is marked. The liner part is described by using Lagrangian framework when the shell, explosive, ES, waveguide and air are described by using Eulerian framework [7]. The mesh in the present paper used a regular cell with size of 0.5×0.5 mm/cell [11], and the numerical results are grid independent.

In addition, the fluid–solid coupling algorithm is applied to catch the interaction between different parts. 2D axisymmetric model (about X-axis) is used for reducing the computation cost. The symmetrical inhibiting condition is added to the symmetrical surface of the model to restrict the displacement and rotation degrees of freedom of node [14,15]. And it is needed to add a flow boundary to the boundary of air in order to eliminate the influence of the waves reflected from an interface.

A typical ES is shown in Fig. 1, where R_1 is expressed as the top radius of ES, R_2 is expressed as the bottom radius, H_1 is expressed as

the height of frustum of a cone, and H_2 is expressed as the height of ES. The whole EFP warhead is placed in the air, the diameter and length of the warhead are 100 mm, respectively; the thicknesses of bottom wall and circumferential wall of the EFP warhead are 5 mm and 4 mm, respectively; the thickness and diameter of waveguide are 1 mm and 9 mm, respectively; and the bottom of ES is 6 mm from the bottom of the explosive in the warhead.

2.3. Numerical method verification

The numerical method is first verified by redoing the case and performing the experimental case in Ref. [7]. Numerical model, experimental model and experimental layout are shown in Fig. 2 (a), (b) and (c), respectively.

The diameter of EFP warhead in Fig. 2 (b) is 155 mm. The wooden support in Fig. 2 (b) is a supporting device when the EFP warhead is initiated. The function of wooden support is to minimize the influence of external force on EFP warhead during the initiation, and make the initiation state much more similar to the real scene where a terminal sensitive projectile EFP warhead initiates in the air, and the wooden support is used. The shape target in Fig. 2 (c) is used to measure the shape of EFP, and the velocity target in Fig. 2 (c) is used to measure the velocity of EFP.

The EFP sizes and velocities obtained by simulation and experimental measurement are compared in Fig. 3 and Table 7, respectively.

As shown in Fig. 3 and Table 7, the numerical results can meet the experimental results well, with relative difference of less than 10%. Hence, it should be reasonable to apply the given numerical method to perform simulation.

2.4. Numerical simulation scheme

5 cases were designed to analyze the propagating range of detonation wave as keeping the volume of ES fixed, $R_1 + H_1 = 0.15D$ (D : diameter of EFP warhead), $R_2 - R_1 = 0.08D$, where R_1 is changed from $0.05D$ to $0.13D$, and α is defined as the value of H_2/R_2 . The values of α and corresponding R_1 , H_1 , R_2 , H_2 and the shape of ES are shown in Table 8.

3. Results and discussion

3.1. Numerically simulated results

The numerical results in Ref. [7] shows that the shape, structure and velocity of EFP are unchanged after $300\mu s$ of detonation and that had been proved by experiments.

The length-diameter ratio (l/d) of EFP is the ratio of the largest length of EFP to the largest diameter perpendicular to it.

Table 9 lists the velocity, l/d and shape of EFP in different cases.

3.2. Velocity and shape of EFP

The velocities and shapes of EFP under different α are listed in Table 9. It can be found from Table 9 that the maximum velocity of EFP is obtained for $\alpha = 1.5$, but the difference between the maximum (1788 m/s) and minimum values (1763 m/s) of EFP velocity is less than 1.5%, so the effect of ES on the velocity of EFP can be ignored. Therefore, it can be deduced that the characteristic

Table 1
Main parameters of copper.

$\rho/(\text{g}\cdot\text{cm}^{-3})$	$C_1/(\text{m}\cdot\text{s}^{-1})$	S_1	G/GPa	A/MPa	B/MPa	n	C	m	γ_0	T_m/K	T_r/K
8.93	3940	1.489	46	0.09	0.292	0.31	0.025	1.09	2.02	1356	293

Table 2
Main parameters of aluminum.

$\rho/(\text{g}\cdot\text{cm}^{-3})$	$C_1/(\text{m}\cdot\text{s}^{-1})$	S_1	G/GPa	A/MPa	B/MPa	n	C	m	γ_0	T_m/K	T_f/K
2.785	5328	1.338	27.6	0.265	0.426	0.34	0.015	1	2	775	293

Table 3
Main parameters of 45# steel.

$\rho/(\text{g}\cdot\text{cm}^{-3})$	$C_1/(\text{m}\cdot\text{s}^{-1})$	S_1	G/GPa	A/MPa	B/MPa	n	C	m	γ_0	T_m/K	T_f/K
7.84	4570	1.49	80	0.5	0.32	0.28	0.064	1.06	1.93	1790	293

Table 4
Main parameters of 8701.

$\rho/(\text{g}\cdot\text{cm}^{-3})$	$A/10^8\text{kPa}$	$B/10^8\text{kPa}$	$R1$	$R2$	ω	$D/10^3(\text{m}\cdot\text{s}^{-1})$	$E_0/10^6(\text{kJ}\cdot\text{m}^{-3})$
1.70	8.54	6.2049	4.60	1.35	0.25	8.315	8.5

Table 5
Main parameters of POLY-CARB.

$\rho/(\text{g}\cdot\text{cm}^{-3})$	$C_1/(\text{m}\cdot\text{s}^{-1})$	S_1	$G/10^5\text{kPa}$	$A/10^4\text{kPa}$	γ_0	T_f/K
1.7	1933	2.65	10.0	8.06	0.61	293

Table 6
Materials and EOSs of the parts of EFP warhead.

Part	Material	EOS
Air	Air	Ideal Gas
Liner	Copper	Shock
Waveguide	Aluminum	Shock
Shell	45# steel	Shock
Explosive	8701	JWL
ES	POLY-CARB	Shock

affecting the velocity of EFP, such as the sort and mass of charge, the configuration, size and material of liner, the material and thickness of warhead shell, were not changed. It can be found that the tail of EFP will be greatly affected by the characteristic parameter of α when the ES consists of the cylinder and frustum of a cone and the volume of ES is fixed. With the decrease in α , the ES is flattened, and the detonation wave propagating through the ES gradually changes from a spherical wave to a planar wave. As a result, the detonation wave changes the aerodynamic shape of the EFP tail. With the decrease in α , a pit gradually appears in the EFP tail firstly, and then a hump gradually appears, finally a hump gradually disappears. The shape of EFP in Case 2 is ideal, the pit in the EFP tail can effectively improve the aerodynamic shape of EFP and reduce the loss of velocity of EFP, thereby enhancing the combat effectiveness.

3.3. Length-diameter ratio of EFP

The l/d and shape of EFP under different α are shown in Fig. 4. It can be found from Fig. 4 that the largest l/d is 2.76 for $\alpha = 1.5$, and the difference among the other cases is below 5%. Comparing with the propagation and pressure field of detonation wave in Case 2 is more compact. As a result, the more uniform pressure field makes the final EFP forming more satisfactory, with greater length-diameter ratio and better combat effectiveness.

3.4. Comparative analysis of detonation wave propagation

In order to characterize the propagation process of detonation wave, the simulated results within 10 μs after detonation are recorded. And the pressure contour plots of detonation wave propagation process in different cases are shown in Table 10. The variable t in Table 10 represents the time after detonation.

Through the comparison of detonation wave propagation process in Table 10, it can be found that the propagating range and pressure field of detonation wave are almost the same for $t = 2\mu\text{s}$. Furthermore, the propagating range and pressure field of detonation wave in ES are closely related to the value of R_1 , specifically when the value of R_1 is smaller than the diameter of the detonation front, the propagating range and pressure field of detonation wave inside and outside of ES will be clearly demarcated. When the value of R_1 increases to be equal to the diameter of detonation front, the boundary distinguishing the propagating range of detonation wave and the boundary distinguishing the pressure fields inside and outside of the ES begins to fade. But ES has an obvious obstructive

Fig. 1. Finite element model of a typical ES used in terminal sensitive projectile (unit: mm).

parameter of α discussed in the present paper has little effect on the velocity of EFP when the ES consists of cylinder and frustum of a cone and the volume of ES is fixed. This is because the main factors

Fig. 2. Numerical model (a), experimental model (b) and experimental layout (c) (unit: mm).

Fig. 3. The diameter of EFP in simulation and result of the shape target (unit in left: mm, unit in right: cm).

Table 7
The diameter and velocity of EFP in experiment and simulation.

	Diameter/mm	Velocity/(m·s ⁻¹)
Experiment	54	1621
Simulation	56.62	1732
Difference rate	4.9%	6.8%

effect on the propagating range of detonation wave.

When $t = 4\mu\text{s}$, the propagation patterns of wave in different cases become significantly different. The propagating range of detonation wave increases with the decrease in α . The reason is that the length of ES along the central axis of warhead decreases with the decrease in α ; and then the obstructive effect of ES on the

Table 8
The values of α and corresponding R_1 , H_1 , R_2 , H_2 and the shape of ES.

Case	1	2	3	4	5
α	2.3	1.5	1.0	0.7	0.6
R_1/mm	5	7	9	11	13
H_1/mm	10	8	6	4	2
R_2/mm	13	15	17	19	21
H_2/mm	30.2	22	17	14	12.2
Shape					

Table 9
Comparison of the velocity, l/d and the shape of EFP in different cases.

Case	1	2	3	4	5
α	2.3	1.5	1.0	0.7	0.6
$v/(\text{m}\cdot\text{s}^{-1})$	1763	1788	1766	1767	1764
l/d	2.52	2.76	2.43	2.53	2.40
Shape

Fig. 4. The l/d and shape of EFP under different α .

propagating range along the central axis of warhead gradually decreases. As a result, the detonation wave can pass through the ES and propagate to a wider range. The influence of ES on the high-

pressure shock waves range in the front of the detonation wave becomes smaller with the decrease of α . The ES has no effect on the detonation wave that does not go through the ES so the propagating range and pressure field of detonation wave are unchanged. It indicates that the ES can hinder the detonation wave from propagating, and the hindering effect fades as the length of ES in the propagating direction of detonation wave decreases.

When $t = 6\mu s$, the propagating range of detonation wave is basically the same in different cases. The reason is that the high-pressure shock waves in the front of detonation wave has already crossed over the ES, thus the ES has no effect on the high pressure range in the front of detonation wave. However, the detonation pressure field varies greatly depending on the configurations of ES. It can be judged that the ES has an obstructive effect on the detonation wave still propagating in the ES. It can also be found from the pressure contour plot that the ES causes a pressure concentration during propagating of detonation wave, and this concentration is closely related to the value of H_2 . With the decrease in H_2 , the concentration of pressure in the propagating range of detonation wave starts to appear gradually, and the concentrated position is continually getting closer to the high-pressure range in the front of

Table 10
The pressure contour plots of detonation wave propagation in different cases.

the detonation wave propagating range.

When $t = 8\mu\text{s}$, the propagating range of detonation wave is basically the same in different cases. However, the detonation pressure field varies with different values of α . With the decrease in α , the high-pressure range in the front of the propagating range of detonation wave tends to expand. The shape of the high-pressure range in the front of the propagating range of detonation wave is quite different, which can be found from the pressure contour plot with different values of α . The reason is that the detonation wave in the ES was propagated outside of the ES, combined with the detonation wave that propagated outside of the ES, and its propagating range is wider. In the propagating range of detonation wave, the plane wave begins to appear with the decrease in α , for $\alpha = 0.7$. And this kind of plane wave is formed by the detonation wave passing through the ES. The smaller the value of α is, the more obvious the outline of the plane wave is, which corresponds to the conclusion in Ref. [6].

When $t = 10\mu\text{s}$, the propagating range of detonation wave is basically the same in different cases. But the pressure field of detonation wave and the outline of high-pressure range in the front of the detonation wave propagating range vary greatly depending on the values of α . It can be found from the pressure contour plot that the outline of detonation wave passing through the ES is quite different obviously for different values of α . With the decrease in α , the detonation wave passing through the ES gradually changes from a spherical wave to a planar wave, and the outline of the planar wave is very obvious when $\alpha = 0.7$ and $t = 10\mu\text{s}$. It indicates that the values of α have a great influence on the propagation of detonation wave that passes through the ES. And it is believed that the detonation influenced by α of ES may be one of the most important reasons for the different tail shape of EFP in the final result.

4. Conclusions

- 1) When the ES made of POLY-CARB material consists of cylinder and frustum of a cone and the volume of ES is fixed, the values of α discussed above have little effect on the velocity of EFP. The disparities among the velocities in different cases are neglectable because the main factors affecting the velocity of EFP, such as the sort and mass of charge, the configuration, size and material of liner, the material and thickness of warhead shell, are not changed.
- 2) When the ES made of POLY-CARB material consists of cylinder and frustum of a cone and the volume of ES is fixed, there exists the best tail shape of EFP among the values of α discussed above. With the decrease in the value of α , the detonation wave passing through the ES gradually changes from spherical wave to planar wave, where exists a proper shape of the wave which can make a pit in the tail of EFP and it is the best tail shape of EFP. Therefore, a proper value of α of ES can be used to make an

effective use of the detonation wave, get a more reasonable aerodynamic-shaped EFP, and effectively improve the combat effectiveness.

- 3) In the early stage of initiation, the ES can decrease the velocity of detonation wave that go through the ES, so the detonation pressure field become different. The detonation pressure field is different under different α , but the quantitative relationship needs to be explored in further work.

Acknowledgement

The work presented in this paper has been funded by the National Natural Science Foundation of China under No. 11102088, Fundamental Research Funds for the Central Universities under No. 30915118821, and funded by the Specialized Research Fund for the Doctoral Program of Higher Education of China under No. 20133219110019.

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