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Influence of lining materials on the detonation driving of fragments

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Abstract The shape and strength of prefabricated fragments changes to some extent after detonation loading. In this paper, detonation loading process of prefabricated fragments under two types of lining layers was studied and compared with no lining. By observing the recovered fragments, it was found that the inner part of the material was cracked and the shape of the fragments changed significantly. Comparing the two lining materials, the Kevlar/epoxy was better protective lining than polyurethane. The detonation process was analyzed qualitatively by using shock wave theory. In order to further explore the process, the simulation software LS-DYNA was used to carry out 3D simulation. The simulation results, in good agreement with the experimental results, showed that the Kevlar/Epoxy liner had a great influence on the initial velocity of the fragment. The experimental results and simulation results suggest that spherical fragments are better than cylindrical fragments in detonation drive application.

1. Introduction

Fragment generator warhead (FGW) is the most popular type of warheads. Detonation wave is generated by explosive detonation, it propagates into the shell, causing it to expand and break and form fragments. The FGW relies on shockwave overpressure and fragments for damage. The former is mainly aimed at the near field targets, while the latter is aimed at the far field targets. At present, researches are mainly focused on the structure, spatial dispersion (projection angle, velocity), damage efficiency of the FGW, aiming to optimize the damage ability of warheads.

Since the 1940s, extensive researches have been conducted on the initial velocity of fragmentation. Gurney estimated the fragmentation velocity under detonation loading based on one-dimensional hypothesis, energy conservation and momentum conservation. A relationship between fragment velocity with charge mass, shell mass and explosive energy was obtained [1]. Due to the simple assumption and the lack of consideration of shell material, this method could only estimate the fragment velocity with relatively large error. Based on Gurney's work, scholars conducted further investigation on the estimation of the initial velocity of fragments. Cullis et al. found that the maximum velocity of naturally broken fragments was inconsistent along the axial [2]. Grisaro et al. used 2d finite element method (FEM), 3d FEM and smoothed particle hydrodynamics (SPH) methods to simulate the process of detonation loading on a cylindrical shell, and obtained the distribution of fragmentation velocity in the axial direction [3]. As Gurney ignored the influence of lateral sparsity effect, some scholars modified Gurney's formula by adding modification factors. Their results were highly consistent with the experiment. While all of these studies focused on the velocity of the fragments on the cylindrical surface, Waggner et al. paid attention to the end of the cylinder [4]. On this basis, Lloyd et al. developed the relation expression between fragment velocity and radial distance [5]. Dhote et al. carried out an experimental study of single-layer and multi-layer fragments by detonation ignited in end center. They explained the deformation and acceleration process using one-dimensional shock wave theory [6]. The results on fragmentation velocity distribution was consistent with Lloyd R's earlier work.

The fragments of FGW mainly include three types: natural fragments, pre-controlled fragments and prefabricated fragments [7-9]. For prefabricated fragments, a large number of scholars considered them as rigid bodies during detonation, the deformation and fracture behaviors of fragments during detonation loading was ignored. In fact, it was found that the shape and internal microstructure of prefabricated fragments change to some extent after detonation loading. This change may have a small influence on the velocity and dispersion field of the fragments, but a great influence on the damage effect.

Mirmomeni et al. studied the mechanical properties and fracture behavior of low carbon steel under high strain rate loading and subsequent high temperature environment [10, 11]. Their results showed that the dynamic behavior of the material at high temperature is quite different with that at room temperature. Mehditabar et al. analyzed response of functionally graded cylindrical shell under magneto-thermo-elastic interaction condition [12]. The differential quadrature method (DQM) was proposed to discretize the existing partial differential equations and transform them to a set of algebraic equations. Their results showed that the properties of functionally graded materials are heterogeneous along thickness and appropriate inhomogeneity constant n control the amplitude of the stress components and the perturbation of the magnetic field vector. Beyond that, they conducted experiments and simulations about functionally graded materials under two different loading [13]. Donoghue et al. conducted a two-dimensional simulation and experimental study on the dynamic response of prefabricated fragments during detonation loading. The simulation results were in agreement with the test results [14]. The results suggested that under the detonation loading, spalling, micropore nucleation, growth and cracks will occur in the prefabricated fragments. Anderson et al. conducted relevant studies on explosion-loaded tungsten fragments, finding that spalling failure caused by the aggregation of micropores occurred in tungsten alloys under detonation loading [15-17]. The stress on the central axis of the fragment is greater than that on both sides. When the tensile stress inside the fragment is greater than the exfoliation stress of the material, the spalling failure occurs. A novel experimental technique was developed to quantify the loading from a blast-driven ball bearing in Qi et al. study [18]. Their results showed the critical influence of charge mass and aspect ratio on the development of the detonation pressure profile, its interaction with the embedded bearing, and the flight characteristics of the bearing. In the same way, the deformation of bearing was witnessed.

It is concluded from earlier study that the prefabricated fragments are damaged under detonation loading. Its morphology also changes significantly. This change is obviously due to the high temperature and high-pressure of the shock wave. In warhead design, lining materials are sometimes used to avoid ultra-high-pressure influences or to change the shape of shock wave. Cheng et al. investigated the influence of aluminum foam lining on deformation of steel cylinders subjected to internal blast loading by experiment and numerical simulation [19].

The study suggested that the aluminum foam lining with enough thickness will reduce the deformation of the steel cylinders, however, if the thickness of the aluminum foam lining is insufficient, there may be an opposite effect. Mouritz listed several significant studies discussing polymeric composite materials subjected to blast mitigation, where design parameters that lead to the improvement of blast resistance were explored [20].

Based on the above considerations, two kinds of lining were used in this paper to conduct experimental research on the dynamic response of the fragments driven by detonation.

2. Experiment design

The shape of fragments manufactured by AISI45 steel without heat treatment was cylindrical ($\Phi 11$ mm $\times$ H 11 mm) and spherical ($S\Phi 11$ mm). The fragment layer arrangement was hexagonal dense arrangement, as shown in Fig. 1(e). In order to ensure the stability of the initial state of the fragments, epoxy was used to encapsulate the fragments. Due to the weak strength of epoxy, the binding force on the fragments during the detonation process could be ignored.

The samples used in the experiment are shown in Figs. 1(a)-(d). In order to investigate the effect of lining material on the fragment deformation by detonation ignited in end center, two types of linings (polyurethane and Kevlar/epoxy composite) were set in experiment, both of which were 10 mm thick. Polyurethane, whose density is 1.1 g/cm³, is industrial product; Kevlar/epoxy composite, whose density is 1.67 g/cm³, is a laminated material which is made refer to Ref. [21]. In order to incarnate the effect of lining on the fragment deformation, a set of contrast tests without lining was conducted. Moreover, in order to guarantee the single variable, the distance between the fragmentation layer and the end face of the explosive was the lining thickness. The test arrangement is listed in Table 1. The warhead structure is shown as Fig. 2(a). High energy explosive (8701) was placed inside a nylon shell with inner diameter of 60 mm and thickness of 5 mm. In the test, the end face center point detonation method was adopted. Therefore, a column booster with a diameter of 15 mm and a height of 5 mm was placed between the explosive and electric detonator.

The experiment layout is shown in Fig. 2(b). Twenty layers of planks were placed 0.2 m away from the warhead to recover the fragments. In addition, the warhead axis passed through

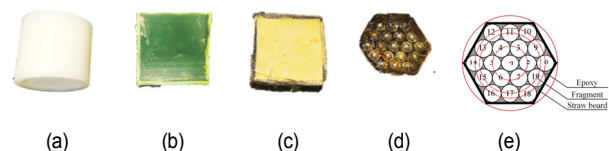


Fig. 1. Test samples: (a) nylon shell and column charge; (b) polyurethane; (c) Kevlar/epoxy composite; (d) fragmentation layer (epoxy packaging); (e) fragmentation arrangement (red dot dash lines represent that the distances of fragments from center are same, while red solid line is the boundary of charge).

Table 1. Experiment arrangement.

No.	Fragment type	Lining type	Count
1#	AISI 45 steel sphere	Polyurethane	7
2#	AISI 45 steel cylindricity	Polyurethane	10
3#	AISI 45 steel sphere	Kevlar/epoxy	7
4#	AISI 45 steel cylindricity	Kevlar/epoxy	7
5#	AISI 45 steel sphere	No	11
6#	AISI 45 steel cylindricity	No	11

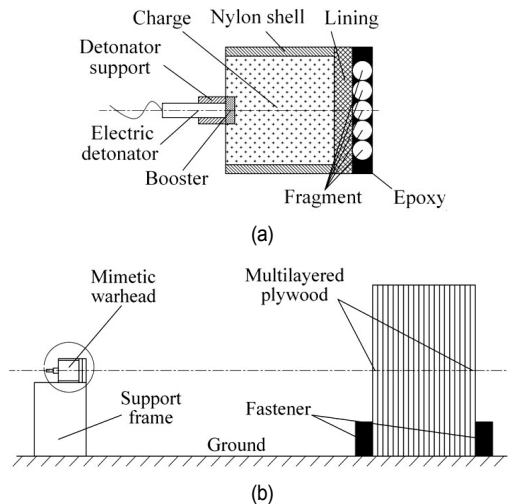


Fig. 2. Experimental design: (a) warhead assembly drawing; (b) experiment set-up.

the plank midpoint.

After the detonation, all the recovered fragments were weighed. Afterwards, a flake sample with a 2 mm thickness was cut along the symmetrical plane of deformation fragmentation. The deformed symmetry surface was ground through 180-2500 mesh silicon carbide paper, and then polished by 5 μm and 2.5 μm diamond suspension. After grinding, 4 % nitrate alcohol solution was used for etching. Finally, field emission scanning electron microscopy (SEM) and electron backscattered diffraction (EBSD) were used to analyze the microstructure.

3. Experimental results and analysis

3.1 Macroscopic deformation of fragments

Explosive detonation could produce high pressure of up to tens of GPa and high temperatures of thousands of Kelvin, which is an extreme condition. After being subjected to the effects of the explosion, the fragments underwent rapid severe deformation. This process was very short, lasting only a few tens of microseconds. Fragmentation deformation was a rapid dynamic response process of metal materials under high temperature and high pressure. The degree of deformation depended on the strength of the material and the energy of explosive. In end face detonation test, when detonation wave was

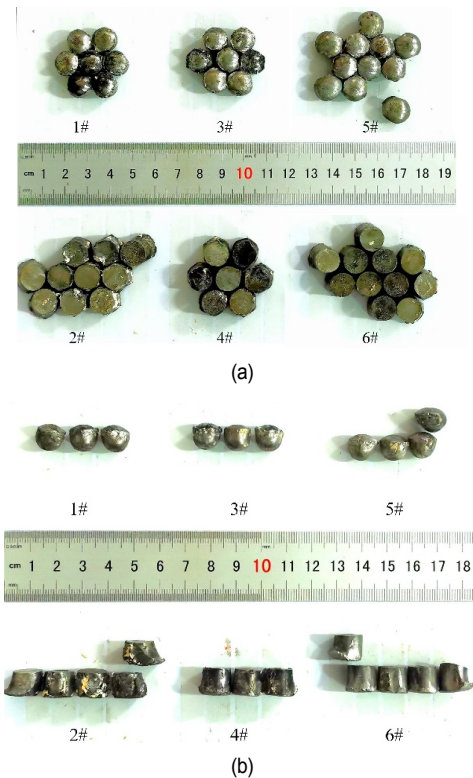


Fig. 3. Macroscopic deformation of fragments: (a) front view (all recovered fragments); (b) side view (partial recovered fragments).

transmitted from one end of the explosive to the other end, the wave front was spherical in shape. For the fragments at different positions, the magnitude and direction of the detonation wave pressure was different, so the deformation mode was also different. The front view of all fragments recovered in the test and the side view of some fragments are shown in Fig. 3.

It is shown in Fig. 3 that the influence of different lining materials on the deformation of the fragments is obvious under detonation drive. As shown in Fig. 3(b), from a side perspective, the deformation degree of all recovered fragments (not only the central fragment) in 3# and 4# test is smaller. Linings played a role in regulating the detonation wave but did not change the deformation mode of the fragments. Therefore, as shown in the red circle line in Fig. 1(e), the deformation of fragments at the same distance from the center is similar. The fragments at outer radius experienced greater the degree of deformation. As the magnitude and direction of the shock wave pressure at each point on the end face were different, the attitude of the fragments changed gradually during the detonation loading process, the final shape of the recovered fragments, except for the innercircle fragments, couldn't be accurate. The deformation of the innercircle fragments of each experiment was measured. Fragment deformation is quantified as shown in Fig. 4. The measured results are listed in the Table 2. The larger l_x, l_y is and the smaller l_z is, the greater the fragment deformation is. Δd is the average value of the difference between l_x, l_z and the original fragment size, as shown in Fig. 5(a). The

Table 2. Size of recovered center fragments.

Lining / fragment	l_x /mm	l_y /mm	l_z /mm
Polyurethane - sphere	10.69±0.06	11.30±0.02	10.40±0.07
Kevlar/epoxy - sphere	10.73±0.07	11.55±0.14	10.40±0.07
Sphere (no lining)	10.73±0.02	11.61±0.18	10.49±0.13
Polyurethane - cylindricity	11.65±0.07	12.95±0.25	9.77±0.13
Kevlar/epoxy - cylindricity	11.64±0.13	12.70±0.11	10.15±0.13
Cylindricity (no lining)	11.61±0.03	11.98±0.25	10.34±0.13

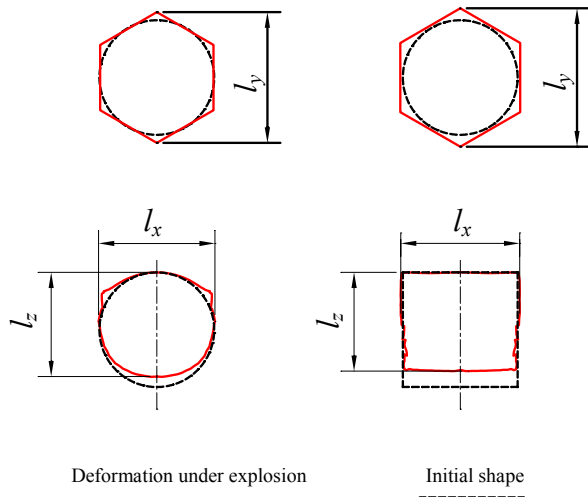


Fig. 4. Deformation quantization diagram.

deformation of spherical fragments and cylindrical fragments was the smallest when there was no lining. In addition, the deformation of fragments was smaller when the lining was Kevlar/epoxy than when the lining was polyurethane. The results show that the explosion resistance of Kevlar/epoxy lining is better than that of polyurethane. Moreover, with the same thickness, the air layer would greatly reduce the shock pressure.

By weighing and analyzing the recovered fragments, the mass loss of the fragments after detonation loading could be obtained. The average masses of recovered fragments are shown in Fig. 5(b). It is shown that although different lining layers have a certain influence on the deformation of the fragments, the masses loss of the fragments are similar. As the detonation loading itself cannot cause significant damage to the fragment. However, the standard deviation of the fragment mass recovered from the tests whose lining is Kevlar/epoxy is the smallest, indicating that the detonation pressure value through the Kevlar/epoxy lining is similar in the whole radial range.

Take polyurethane material as an example and analyze its detonation process using detonation theory. The wave impedance of nylon is less than that of explosive, so the reflection of detonation wave on the shell wall is reflected expansion wave. Considering the direction of detonation pressure applying on the fragments, the reflection of the wave on the shell wall is

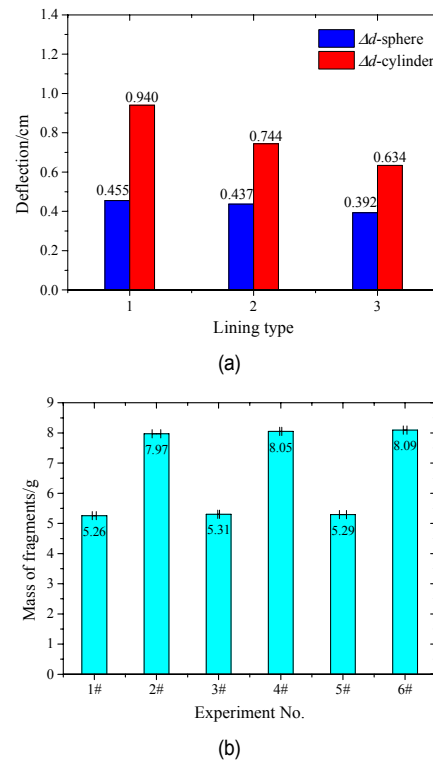


Fig. 5. Macroscopic deformation of recovered fragments: (a) recovered fragments deformation quantization according to Fig. 4 (1 and 2 lining layers are polyurethane and Kevlar/epoxy, respectively, 3 without lining layer); (b) the average and standard deviation of mass of recovered fragments (considering the standard deviation of Exp 3# & 4# very small, error bars are in the x direction; the meaning of experiment No. are same with Fig. 3).

ignored. When detonation wave propagates steadily, the wave front of self-sustaining detonation is spherical. The wave impedance of polyurethane is also lower than that of explosive, so Prandtl-Meyer expansion occurs at the interface between explosive and lining. Its flow diagram is shown in Fig. 6, where OI is the oblique detonation wave front, and ϕ_0 is the angle between OI and the initial interface; OT refers to the oblique transmitted shock wave front, and the angle between OT and the initial interface is ϕ_3 ; The lining material deforms under the action of detonation, and the angle between the moved interface and the initial interface is δ . The oblique incident wave front, oblique reflection rarefaction wave, transmitted wave and interface to the whole flow field is divided into six regions: (0) is the area for unexploded charge, (1) is the area for the detonation product after the oblique detonation wave, (2) is the area for the detonation product expansion, (3) is the area for the detonation product after expansion, (m_0) is the area for initial lining medium, (m) is the area which be disturbed by oblique transmitted wave in lining medium [22].

On the interface between explosive and lining material, the incident wave is detonation wave. Detonation wave front pressure is CJ pressure, whose shape is spherical. The flow of wave on the interface is shown in Fig. 6. Therefore, according

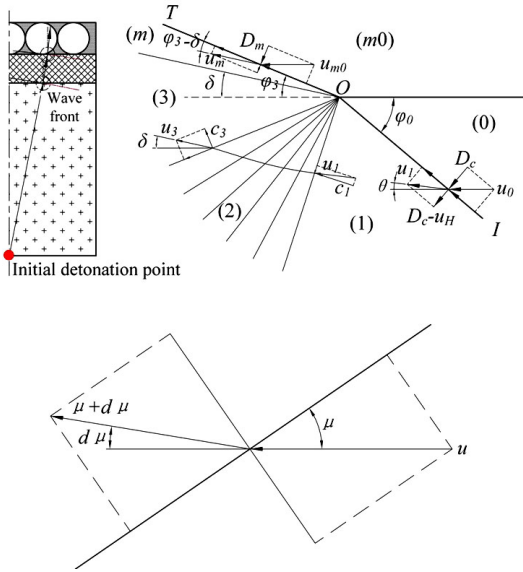


Fig. 6. Detonation flow diagram.

to the conservation and flow law of the detonation wave front, the relationship between the parameters in area (3) and the known parameters is shown in the following Eqs. (1) and (2):

$$M_{a3}^2 = \frac{M_{a1}^2 + \frac{2}{k-1}}{\left[\frac{(k+1)\rho_{m0} \sin \varphi_3 \left(\frac{\sin \varphi_3}{\sin \varphi_0} - \frac{a}{D_c} \right) \right]^{\frac{k-1}{k}}} - \frac{2}{k-1} \quad (1)$$

$$\begin{aligned} & \left[\sqrt{\frac{k+1}{k-1}} \arctg \sqrt{\frac{k-1}{k+1} (M_{a3}^2 - 1)} - \arctg \sqrt{M_{a3}^2 - 1} \right] - \\ & \left[\sqrt{\frac{k+1}{k-1}} \arctg \sqrt{\frac{k-1}{k+1} (M_{a1}^2 - 1)} - \arctg \sqrt{M_{a1}^2 - 1} \right] + \theta \\ & = \arctg \left[\frac{\left(1 - \frac{a \sin \varphi_0}{D_c \sin \varphi_3} \right) \lg \varphi_3}{b + \left(b - 1 + \frac{a \sin \varphi_0}{D_c \sin \varphi_3} \right) \lg^2 \varphi_3} \right] \end{aligned} \quad (2)$$

where, k is the adiabatic index of detonation product.

$$\begin{cases} k = 1.25 + k_0 (1 - e^{-0.546 \rho_0}) \\ k_0 = \frac{\sum_{i=1}^L \mu_i}{\sum_{i=1}^L k_{0i} M_i} \end{cases} \quad (3)$$

k_0 , which is related to density, is a part of k ; ρ_0 is the density of the mixed explosive (g/cm^3); μ_i is the mass percentage of component i of mixed explosive; M_i is the molar mass of component i of mixed explosive; k_{0i} is k_0 of component i of the mixed explosive. The composition of the explosive is listed in Table 3.

Table 3. Composition and mass fraction of the explosive [23].

μ (RDX) %	μ (dinitrotoluene) %	μ (vinyl acetate) %	μ (stearic acid)
95	3	2	trace

Table 4. The material parameters used in calculation.

$\rho_{m0}/\text{g}\cdot\text{cm}^{-3}$	$\rho_0/\text{g}\cdot\text{cm}^{-3}$	$a/\text{m}\cdot\text{s}^{-1}$	b	$D_c/\text{m}\cdot\text{s}^{-1}$	k_0/RDX	$k_0/\text{vinyl acetate}$	$k_0/\text{dinitrotoluene}$
1.1	1.68	2568	1.498	8800	2.65	2.78	2.78

Notice: ρ_{m0} , the density of polyurethane; a & b , the empirical constant of impact compression relation; D_c , explosive detonation velocity; k_0 , which is related to density, is a part of k .

After calculation, the adiabatic index k of 8701 explosive is 2.85.

M_{a3} is the Mach number in the region (3), M_{a1} is the Mach number in the region (1), $M_{a1} = \frac{u_1}{c_1} = \sqrt{1 + \left(\frac{k+1}{k} \right)^2 \lg^2 \varphi_0} \cdot \rho_{m0}$

the initial density of the lining. a and b are the empirical constants of impact compression of lining. D_c stands for explosive detonation velocity. θ is flow deflection angle, $\lg \theta = \frac{\lg \varphi_0}{1 + k(1 + \lg^2 \varphi_0)}$. The values of parameters required for the

above calculation are listed in Table 4.

By combining Eqs. (1) and (2), the value of M_{a3} and φ_3 can be obtained.

The parameters of (m) area can be obtained from Eqs. (3)-(5)

$$\frac{\rho_{m0}}{\rho_m} = 1 - \frac{1}{b} \left(1 - \frac{a \sin \varphi_0}{D_c \sin \varphi_3} \right) \quad (4)$$

$$p_m = \frac{\rho_{m0} D_c^2 \sin \varphi_3 \left(\frac{\sin \varphi_3}{\sin \varphi_0} - \frac{a}{D_c} \right)}{b \sin \varphi_0} \quad (5)$$

$$u_m = \frac{D_c \sin \varphi_0}{\sin \varphi_3} \left[\left(1 - \frac{1}{b} + \frac{a \sin \varphi_0}{b D_c \sin \varphi_3} \right)^2 + \lg^2 \varphi_3 \right]^{\frac{1}{2}} \quad (6)$$

In the formula, ρ_m , p_m , u_m are the state parameters of the medium after the wave. The transmitted wave velocity is:

$$D_m = \frac{D_c \sin \varphi_3}{\sin \varphi_0}$$

. After wave front passes through the interface, the velocity and the direction of it are solved.

Based on the above solutions, the shape of the wave front in the explosive and polyurethane lining can be calculated, as shown in Figs. 7(a)-(c). After detonation wave passed through the interface between explosive and lining, its shape and pressure changed. As shown in Figs. 7(b) and (d), at $t = 7.23 \mu\text{s}$, the shape is deflected to some extent as it crosses the interface, resulting in a smoother overall view of the waveform. As a result, detonation pressure on the fragment would be more uniform and dispersion angle would be smaller.

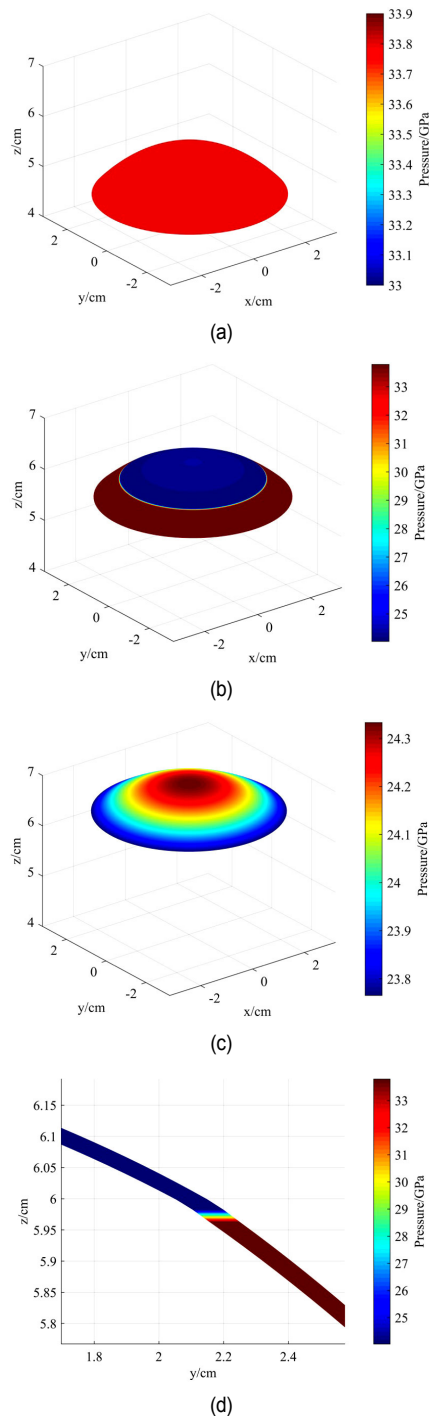


Fig. 7. The shape and pressure of the detonation wave change as it passes through the explosion-lining interface: (a) $t = 6.25 \mu\text{s}$, $\Delta z = 0.89 \text{ cm}$; (b) $t = 7.23 \mu\text{s}$, $\Delta z = 0.68 \text{ cm}$; (c) $t = 8.20 \mu\text{s}$, $\Delta z = 0.54 \text{ cm}$; (d) partial enlarged drawing about shape change at $t = 7.23 \mu\text{s}$ (Time was obtained by wave velocity and distance away from the initial detonation point).

When the shock wave propagated through the lining into the fragment (cylindricity) layer, theoretically, the normal reflection of the shock wave occurred only at the lowest point of the central fragmentation, based on the high coaxiality between lining and charge column. Along the radial direction, the angle of

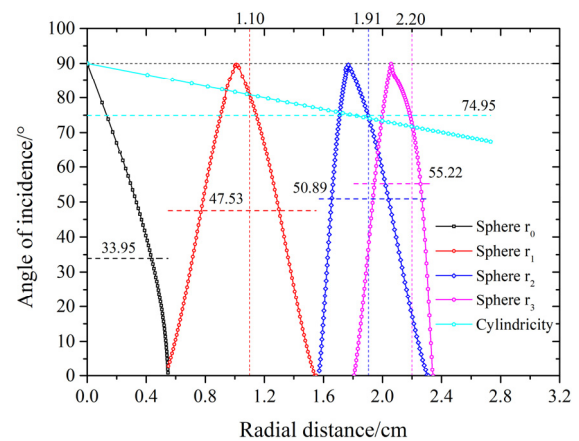


Fig. 8. The angle of incidence of shock wave to fragments. r_0 , r_1 , r_2 , r_3 represent spherical fragment whose distance from center are different. The dash lines are the average of the solid lines of the corresponding color.

incidence is shown in Fig. 8. Therefore, in this experiment, the collision between shock wave and fragment layer was oblique reflection. According to the principle of shock wave transmission and reflection at the interface, there were two situations. One was the shock wave entering the fragment from the lining, from a weak medium into the strong medium; the other was shock wave entering the epoxy from the lining, both weak medium. According to the conservation of mass of the wave flowing at the interface, the velocity of the particle after the wave in the fragmentation decreased, while that of the epoxy essentially unchanged. It was continuous at the interface between the fragments and the epoxy. The first half of the spherical fragments was compressed by shock wave pressure, and the second half was stretched by shock wave transmission and reflection. On one hand, this stretching action resulted in the spall damage inside the fragment; on the other hand, the velocity difference of post-wave particles at the edge of the fragment was larger. The deformation process of cylindrical fragmentation was different from that of spherical fragmentation due to its shape. Relative to detonation wave, the center fragment was symmetric and its shape was unchanged. Therefore, the upsetting of the front part and the deformation of the back part occurred. Except for the central fragment, the position relationship between other fragments and the detonation wave was uncertain, so the deformation modes were different from that of the central fragment. As shown in Fig. 8, the change law of the angle of incidence along the radius direction is different with the shape of fragments. There is one normal reflection point in each fragment when the near-spherical wave front contacts the surface of fragment. However, it decreases rapidly to zero. On the contrary, the angle of incidence in cylindrical fragments situation decreases slowly. According to the law of the transmission and reflection of shock wave, the pressure after wave decreases with decreasing angle of incidence. Thus, the force of each spherical fragment suffered is lower than cylindrical fragment. It results to the degree of deformation of spherical fragments smaller than that of cylindricity.

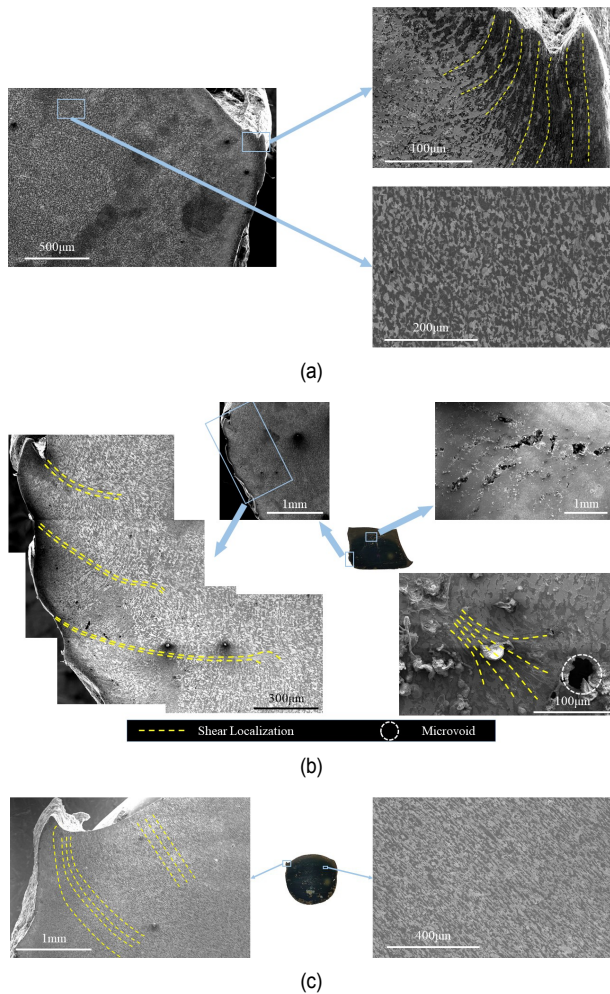


Fig. 9. Internal microscopic deformation of fragments: (a) central fragment of 1#, (b) outmost fragment of 2#, (c) central fragment of 3#.

3.2 Microscopic deformation of fragments

From the macroscopic deformation of the fragments, it was shown that the deformation was not uniform, so the microscopic analysis was carried out. Fig. 3 shows that there is a symmetry plane in the deformed fragmentation. The symmetrical plane is the longitudinal section of the fragment, which is the maximum deformation plane of the fragments. The fragments were cut along the longitudinal section and analyzed by SEM and EBSD.

The cross-section microstructure of recovered fragments is shown in Fig. 9. Grains at the edge of the fragment elongate and grow along the same direction, suggesting that significant plastic flow occurs at the edge of the fragment. At the central position of the fragment, the grain size is uniform and its arrangement is regular, which suggests that the shock wave has little influence on the center part of the fragment. But it does not mean that the shock pressure in the middle part is low. In fact, since there is no rarefaction effect in the center of the fragment, the pressure should be higher than that on both sides of the fragment. The spall failure in the center of the fragment also

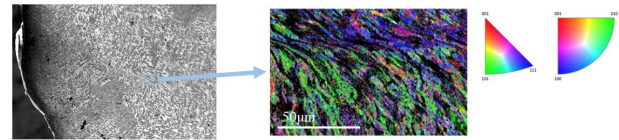


Fig. 10. EBSD analysis of strain localization.

supports the above idea. Donoghue et al. found in their study of the detonation driven tungsten alloy fragments that the spall occurs inside the fragments [14]. SEM observation was conducted on the spall region, as shown in the Fig. 9(c). The spall site is composed of many voids and cracks. There is obvious strain localization between holes and cracks. Based on the previous studies on crack growth, strain localization is the precursor of crack formation. The EBSD analysis result about the strain localization is showed in Fig. 10. It proves that grain elongation exists obviously in the region of strain localization, but preferential crystal orientation does not exist as strong texture was not observed.

The grain elongation occurred in the edge of the fragments. According to the above analysis, the particle velocity at the edge of the fragment is larger than that at the middle of the fragment. However, the difference does not cause local deformation of the fragments. In previous work by Anderson and Donoghue et al. [14, 17], they investigated deformation and failure in fragments under dynamic launch process. It was shown that impact velocities increase from zero at the bottom (where the adjacent fragment is touching) to 1 km/s at the top. The impact is also at a slightly oblique angle, with the result that there is a shear component to the impact force. This results in considerable deformation along the fragment edge, where the flow of the metal is easily discerned, and in fact, the fragments can impact weld together, and separate later due to the geometrically divergent fragment trajectories.

4. Simulation

4.1 Simulation model

Commercial finite element simulation software LS-DYNA was used to numerically simulate the process of detonation driven fragmentation. Generally, the simulation of explosive loading is implemented in three forms: common node method, sliding detonation method and fluid-structure interaction (FSI). The surfaces of explosive and the surfaces of fragments at interface should be common with nodes in common node method. Sliding contact type is adopted in sliding detonation method, which requests the shape of interfaces between explosive and fragments is same. Based above reasons the first two methods were not suitable for the simulated test situation in this paper, so the FSI method was adopted to simulate detonation in this paper.

In the test, as shown in Fig. 2(a), the simulated warhead mainly consists of five parts: booster, charge, nylon shell, lining and fragments, of which the fragments are encapsulated in

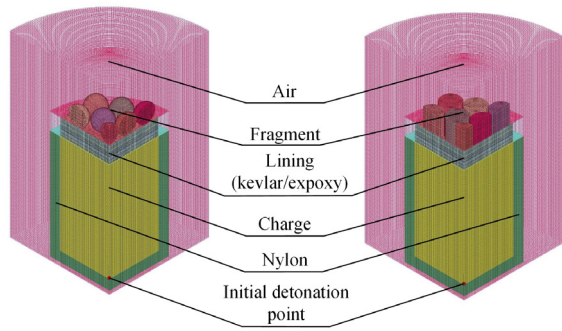


Fig. 11. Simulation model.

epoxy. The FSI method of LS-DYNA requires the use of arbitrary Lagrange-Euler (ALE) elements for simulation. The booster, charge, weaker lining, epoxy, nylon and air in the simulated model needed to be modeled using ALE elements [24]. The simulation model was simplified based on the reality of the experimental design. It mainly included: canceling the part of the booster in the simulation model and the initial detonating point directly in the end face center of the explosive; omitting the layer of epoxy material. In order to ensure the consistency of the simulation model, the fragmentation layer was placed in the same position in the comparison test. Taking Kevlar/epoxy composite lining as an example, the simulation model is shown in Fig. 11.

4.2 Material model

Undergoing high temperature and high-pressure loading, metal material produced great plastic strain with high strain rate. Therefore, it was very important to select the constitutive model of material. In addition, in order to reproduce the deformation process of fragments, the mesh of fragments was set as 0.3 mm. In the calculation of LS-DYNA software, the size of Lagrange grid and ALE grid, which was 0.4 mm should not have a large discrepancy. Thus, the meshes of the entire model were relatively small, led to a large number of meshes. Under the equilibrium of the large number of meshes and the simulated defects relative to the ultra-high strain rate, we chose the isotropic and kinematic hardening plasticity model (*MAT_PLASTIC_KINEMATIC) as the constitutive model of AISI45 steel. It could improve computational efficiency. Furthermore, in LS-DYNA, the effect of strain rate could be considered by the Cowper and Symonds formulation. The material models and their parameters used in the numerical simulation are listed in Table 5.

The Kevlar/epoxy composite used in the test was a heterogeneous material, which was equivalent to epoxy as the matrix and Kevlar as the reinforcement. According to the Refs. [21, 25, 26], there are usually two methods for the simulation modeling of this kind of material, i.e. the macroscopic homogeneous model and the mesoscale heterogeneous model. The finite element modeling of both is shown in Fig. 12. The difference is that the macroscopic model does not consider the cross-

Table 5. Material parameters used for numerical simulation (cm-g- μ s in unit) [24, 27, 29, 30].

AISI45#steel							
*MAT_PLASTIC_KINEMATIC							
R _O	E	PR	SIGY	ETAN	BETA		
7.83	2.1	0.33	7.55E-3	0.02	1.000		
Charge							
*MAT_HIGH_EXPLOSIVE_BURN							
R _O	D	PCJ					
1.680	0.880	0.370					
*EOS_JWL							
A	B	R ₁	R ₂	OMEG	E ₀	V ₀	
8.524	0.1802	4.550	1.300	0.380	0.085	1.000	
Air							
*MAT_NULL							
R _O	PC		MU				
1.1845 e-3	-1E-10		1.8444 e-10				
*EOS_LINEAR_POLYNOMIAL							
C ₀	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	E ₀
0	0	0	0	0.4	0.4	0	2.53 e-6
V ₀							
1.0							
Nylon							
*MAT_ELASTIC_PLASTIC_HYDRO							
R _O	G	SIGY					
1.13	2.70 e-2	1.20 e-3					
*EOS_GRUNEISEN							
C	S ₁	S ₂	S ₃	GAMA0	a	E ₀	V ₀
0.257	1.85	0	0	1.08	0.46	0	1.0
Polyurethane							
*MAT_JOHNSON_COOK							
R _O	G	A	B	n	c	m	T _M
1.10	2.20 e-2	5E-4	0	1	0	0	474
*EOS_GRUNEISEN							
C	S ₁	S ₂	S ₃	GAMA0	a	E ₀	V ₀
0.2486	1.577	0	0	1.55	0.46	0	1.0
Kevlar							
*MAT_ENHANCED_COMPOSITE_DAMAGE							
R _O	E ₁	E ₂	E ₃	V ₁₂	V ₁₃	V ₂₃	G ₁₂
1.44	0.185	0.185	6E-2	0.25	0.33	0.33	7.7 e-3
G ₁₃	G ₂₃	X _t	Y _t	X _c	Y _c	S _c	
5.43e-2	5.43e-2	1.85e-2	1.85e-2	1.85e-3	1.85e-3	7.7e-4	

winding of each layer of Kevlar fibers, but treats it as a homogeneous anisotropic material. The Kevlar fibers were modeled and the interaction forces between the fibers was considered in mesoscopic model. Bresciani et al. concluded that both methods can be used to simulate the dynamic response characteristics of composite materials under ballistic impact [27]. The focus

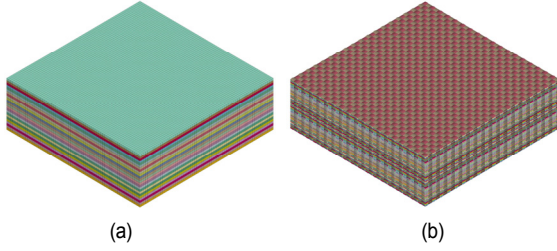


Fig. 12. Kevlar modeling: (a) macro homogeneous model; (b) meso-heterogeneous models.

of this paper was fragmentation deformation, rather than studying the dynamic characteristics of the composite. Therefore, macroscopic homogeneous model was chosen for the simulation of Kevlar/epoxy composites in this paper.

MAT 054/055 (*MAT_ENHANCED_COMPOSITE_DAMAGE) in LS-DYNA was selected for Kevlar/epoxy. The failure of fiber material was considered from two aspects, stress and strain, respectively. Eqs. (7) and (8) are failure criteria of fiber material under tensile and compression conditions; Eqs. (9) and (10) are failure criteria of matrix polymer materials under tensile and compression conditions, respectively [21].

$$e_f^2 = \left(\frac{\sigma_{11}}{X_t} \right)^2 + \beta \left(\frac{\sigma_{12}}{S_c} \right)^2 - 1 \Rightarrow \begin{cases} \geq 0, \text{failed} \\ < 0, \text{elastic} \end{cases} \quad (7)$$

$$e_c^2 = \left(\frac{\sigma_{11}}{X_c} \right)^2 - 1 \Rightarrow \begin{cases} \geq 0, \text{failed} \\ < 0, \text{elastic} \end{cases} \quad (8)$$

$$e_m^2 = \left(\frac{\sigma_{22}}{Y_t} \right)^2 + \left(\frac{\sigma_{12}}{S_c} \right)^2 - 1 \Rightarrow \begin{cases} \geq 0, \text{failed} \\ < 0, \text{elastic} \end{cases} \quad (9)$$

$$e_d^2 = \left(\frac{\sigma_{22}}{2S_c} \right)^2 + \left[\left(\frac{Y_c}{2S_c} \right)^2 - 1 \right] \frac{\sigma_{22}}{Y_c} + \left(\frac{\sigma_{12}}{S_c} \right)^2 - 1 \Rightarrow \begin{cases} \geq 0, \text{failed} \\ < 0, \text{elastic} \end{cases} \quad (10)$$

where, σ_{11} , σ_{12} , σ_{22} are stress components in different directions; X_t is longitudinal tensile strength; X_c is longitudinal compression strength; Y_t is transverse tensile strength; Y_c is transverse compression strength; S_c is shear strength. β is the weighting factor for shear term in tensile fiber mode, $0 \leq \beta \leq 1$.

As shown in Fig. 12(a), each layer of Kevlar is modeled using a single-layer mesh. Use contact type *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK between adjacent Kevlar layers. It could well simulate the mechanical behavior between laminates. At the beginning of the calculation, the contact surface between the adjacent Kevlar layers was tied. When the tendency of relative motion was generated by the force between the two layers, the binding constraint maybe failed. Its failure criterion follows Eq. (11).

$$\left(\frac{|\sigma_n|}{NFLS} \right)^2 + \left(\frac{|\sigma_s|}{SFLS} \right)^2 \geq 1 \quad (11)$$

where σ_n , σ_s are the normal and tangential stress calculated in each time step respectively, while NFLS and SFLS represent the normal and tangential failure threshold stress respectively. If the above Eq. (11) is satisfied, the binding constraint between the Kevlar layers will become invalid. The contact between them degenerates into a face to face contact (*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE). The normal and tangential threshold stresses of Kevlar/epoxy composites are 34.5 MPa and 9 MPa [28], respectively.

In this investigation, the effect of lining on detonation wave propagation was studied, while the lining was in direct contact with the explosive. As a result, the detonation wave came into lining and propagated as soon as it transmitted from explosive. The mode of action was different from that of ballistic impact. The ballistic impact test was that the projectile directly impacted the composite material to generate stress wave, then the projectile penetrated the composite material. Therefore, the influence of epoxy on shock wave propagation was ignored in the ballistic impact test. Taking into account that the transmission and reflection of the detonation wave into the lining interface was for the entire lining composite, the epoxy in the Kevlar/epoxy composite was considered in the modeling. Simulation model is shown in Fig. 11.

4.3 Simulation results

4.3.1 Velocity distribution

Driven by detonation wave and detonation products, the velocity of the end-face prefabricated fragments (spherical and cylindrical) can reach the level of hundreds of meters per second in a very short time. Gurney put forward the calculation formula of fragments velocity driven by cylindrical charge, as shown in Eq. (12) [1].

$$V_0 = \sqrt{2E} \sqrt{\frac{C/M}{(1+C/2M)}} = \sqrt{2E} \left(\frac{C}{M} + \frac{1}{2} \right)^{-1/2}. \quad (12)$$

In the above formula, $\sqrt{2E}$ is Gurney characteristic velocity, which is related to the type of explosive. The approximate calculation formula is $\sqrt{2E} = 0.338 \times D_c$, where D_c is explosive detonation velocity. C and M are the masses of explosive and fragments, respectively.

The above formula is usually used to calculate the initial fragments velocity of warhead, whose fragment is on a cylindrical surface. On the basis of the above Eq. (12), Waggner et al. developed a method to calculate the end face fragments velocity, as shown in Eq. (13) [4]. Similar to the original Gurney formula, this formula could only calculate the maximum initial velocity of the fragments, without considering the impact of the fragment position on the velocity. On this basis, Lloyd et al. studied the relation between the relative center distance of the fragmentation and the fragmentation velocity, as shown in Eq. (14) [5].

$$V_M = \sqrt{2E} \frac{\sqrt{3}C/M}{[(C/M+4)(C/M+1)(1+2L/D)]^{\frac{1}{2}}} \quad (13)$$

$$\frac{V}{V_c} = \frac{2}{3} + \frac{1}{3} \sqrt{1 - (r/r_{\max})^2} \quad (14)$$

where, L is the height of the charge; D is the diameter of the charge; r is the radial distance between a fragment center with charge's axle wire; $r_{\max}$ is the charge's radius, $r_{\max} = D/2$; $V_M = V_c$ is the maximum initial velocity of the central fragment.

Eqs. (13) and (14) are used to calculate the relation between fragmentation velocity and distance in the radial direction of charge. The results suggest that a velocity degradation exists in the radial direction along the warhead. This decrease in velocity is somewhat parabolic or elliptical in the radial direction.

Dhote [6] also observed the similar relation between the fragmentation velocity and the radial distance, which proved the correctness of the above formula in calculating the fragmentation velocity relation. The situation in this paper had a certain deviation from the assumption of Lloyd formula. Firstly, the fragments in the condition above two formulas were closely fitted to the end face of the explosive. Theoretically, the effect of the gap on the fragments' initial velocity was not calculated. Secondly, the effect of fragment shape on the fragmentation velocity was not considered. The influence of the fragment materials on the transmission and reflection of detonation wave was also not taken into account.

It is widely believed that the fragments acceleration under detonation loading is mainly divided into two stages, namely, shock wave acceleration and detonation products acceleration [31]. When there was a lining between the fragments and the explosive, the shock wave needed to pass through the lining firstly and then entered into the fragment, leading to the state parameters of the medium after the wave being different. In addition, the lining also impeded the expansion of detonation products. In order to study the influence of a unique variable (lining type) on the detonation driving of fragments, the fragments were placed 10 mm away from the end face of the explosive in the comparative test. Therefore, there was a 10 mm air gap. Through numerical simulation, the dynamic acceleration and deformation of the fragments under detonation loading were obtained. Taking the central fragment under polyurethane lining as an example, the acceleration process of spherical and cylindrical fragmentation is shown in Fig. 13(a). There is a high consistency in the process of fragmentation acceleration. According to Fig. 8 and above analysis, the force of cylindrical fragment suffered is larger than that of spherical fragment suffered. The final velocity of cylindrical fragmentation is higher than that of spherical fragmentation.

The relation between fragmentation velocity and radial distance from the center of the circle is shown in Fig. 13(b). Similar to Fig. 13(a), the velocity of cylindrical fragment is greater than that of spherical fragment. It is shown in Fig. 13(b) that the lining obviously affects fragment velocity. Moreover, the velocity decreases with increasing radial distance. As men-

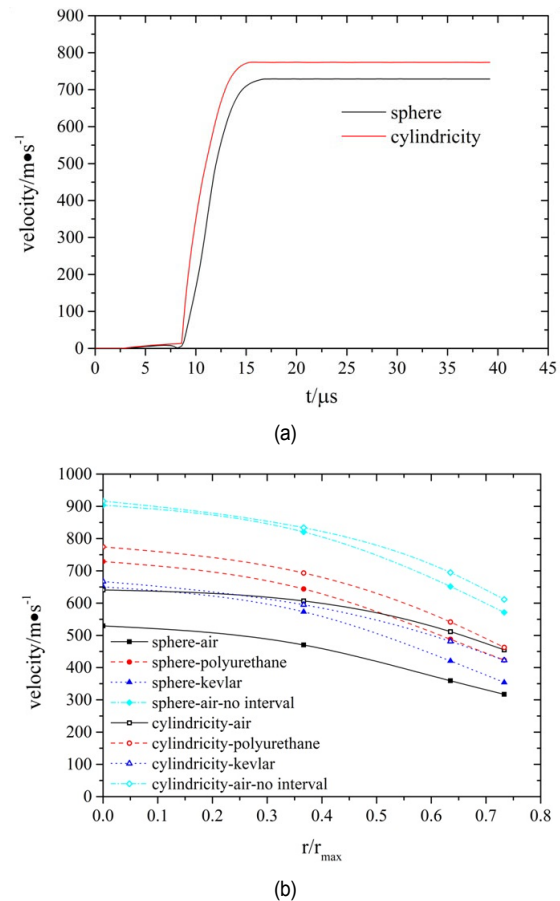


Fig. 13. Fragmentation velocity: (a) the relationship between fragmentation velocity and time in the case of polyurethane lining; (b) maximum initial velocity of fragmentation at different positions ("no interval" means that fragments are next to charge).

tioned above, there were three differences between the actual situation in this paper and the hypothetical situation in the formula, which reduced the maximum initial velocity of the fragment to some extent. In order to explore the influence of fragment position on the initial velocity, the simulation was carried out for the case of no air gap. In the case, the curve of fragment velocity changing with position is shown in Fig. 13(b). By comparing the presence of air gap, it significantly reduces the fragment velocity. There are two aspects in analyzing and summarizing the reasons. Firstly, detonation wave propagates into the air and rapidly attenuates, leading to a great reduction of shock wave pressure on the fragments. Secondly, the detonation products cannot contact the fragments instantaneously during expansion. Moreover, the air gap will also reduce the energy of the detonation products, so the acceleration efficiency is also reduced. Combined with the difference between the hypothesis of Gurney formula analyzed above and the actual situation, the reasons for the decrease of fragment velocity can be attributed to two aspects: the particle velocity difference of fragment after being loaded by shock wave and the acceleration difference of detonation products.

4.3.2 Fragments deformation

After detonation at the end center of the explosive, a spherical detonation wave is generated and spreads outwardly, as shown in Fig. 14, which shows the detonation wave shape and pressure at different time in the numerical simulation. As the wave front propagates to the interface between the explosive and the lining, a reflection at the interface occurs and the wave shape changed at 8 μ s. When the wave front passes through the lining and comes into contact with the fragments, the wave front shape is approximately spherical. So the direction and magnitude of the force on each fragment are not same. At 8.4 μ s, the wave front reaches the interface between the lining and the fragment, with a small error than the 8.2 μ s obtained by above theoretical analysis.

The initial process of cylindrical fragments deformation is shown in Fig. 15. As the wave front passes through the lining, it begins to enter the fragment. Because the boundary of the fragment is in contact with the low impedance medium, it will reflect back to the rarefaction wave and reduce the pressure. At 8.6 μ s-9.2 μ s, the internal pressure of the fragment is larger but the two sides smaller. At 9.4 μ s-10.0 μ s, the reflected wave shape is evident at the right boundary of the outermost fragments. The center part of the fragment is subjected to compression, but both sides of the fragment are subjected to ten-

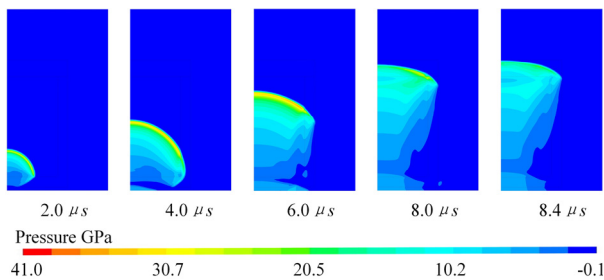


Fig. 14. Detonation process in the simulation.

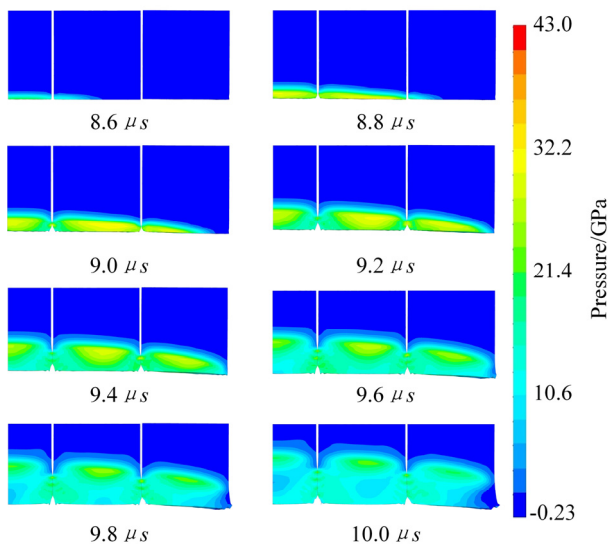


Fig. 15. Initial process of cylindrical fragments deformation.

sion due to the influence of rarefaction wave. In addition, due to the effect of Poisson's ratio, the edge position of the fragment begins to deform, gradually contact and squeeze. After 9.0 μ s, significant pressure is observed at the contact position of the fragment. This contact prevents the radial deformation of the fragment. As the radial direction of the outermost fragment does not have binding force, its deformation is not restrained. As the shock wave travels along the fragments, the area of contact between the fragments increases, the contact pressure decreases.

Due to the spherical wave front of the shock wave, when the shock wave hit the spherical fragments, each fragment still theoretically had a normal impact point. Due to the multiple reflection of shock wave between the fragments and the epoxy, the outer fragments cannot be deformed as symmetrically as the central fragments. It is shown in Fig. 16 that after 10.6 μ s, plastic flow is generated in the contact part of the fragments due to the increase of local velocity, resulting in the deformation characteristics as shown in the Figs. 17(c) and (d). As a result of the radial dispersion of the fragments, the com-

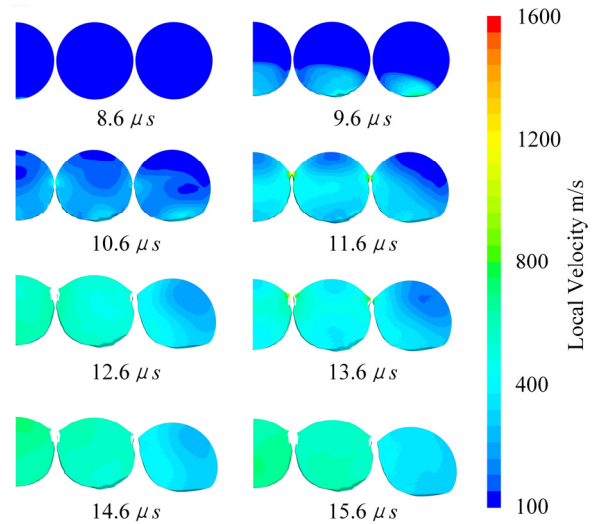


Fig. 16. Local velocity changing process of spherical fragments.

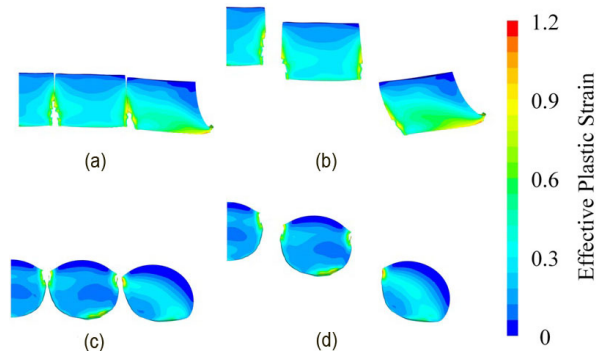


Fig. 17. Fragments deformation results: (a) and (c) 14.6 μ s; (b) and (d) 40 μ s.

Table 6. Size of fragments in simulation.

Lining/fragment	l_x/mm	l_y/mm	l_z/mm
Polyurethane-sphere	11.49 ± 0.04	11.34 ± 0.29	10.46 ± 0.02
Kevlar/epoxy - sphere	11.26 ± 0.02	11.21 ± 0.02	10.56 ± 0.01
Sphere (no lining)	11.11 ± 0.02	11.30 ± 0.03	10.52 ± 0.03
Polyurethane - cylindricity	11.64 ± 0.28	13.18 ± 0.16	9.86 ± 0.03
Kevlar/epoxy - cylindricity	11.45 ± 0.07	12.39 ± 0.14	10.23 ± 0.02
Cylindricity (no lining)	11.32 ± 0.06	12.59 ± 0.12	10.38 ± 0.05

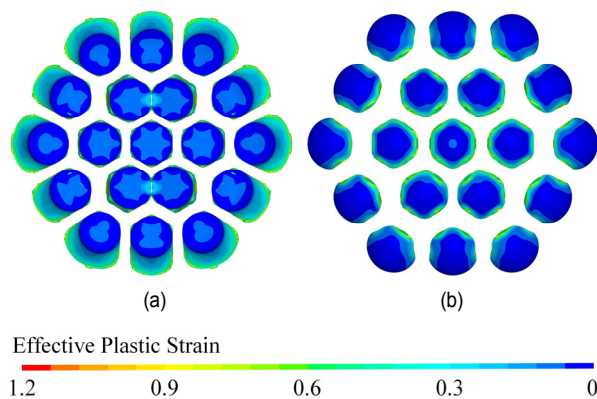


Fig. 18. Radial deformation: (a) cylindricity; (b) sphere.

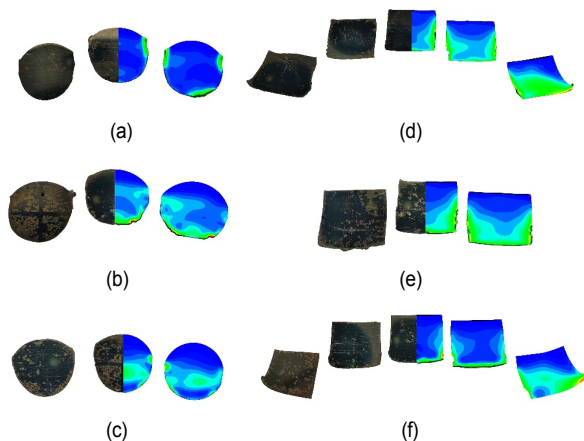


Fig. 19. Comparison of simulation and test results: (a) 1#; (b) 3#; (c) 5#; (d) 2#; (e) 4#; (f) 6#.

pression deformation between the fragments decreases and eventually the separation occurs, as shown in Fig. 17(a). By comparing the deformation of Fig. 17(b), it is shown that the deformation process of the fragment completed at $14.6 \mu\text{s}$. The radial deformation results of the fragments are shown in Fig. 18.

The simulation results on size of recovered fragments are listed in Table 6. Comparison of simulation and test results on the morphology of fragments are shown in Fig. 19. The size of spherical fragments in simulation showed relative large differ-

ence with the experiments results, due to the gap to avoid mesh penetration of adjacent fragments. The deformation pattern of fragments under each lining is similar, and the simulation well reproduced the test results but the deformation degree is different. Comparing Figs. 19(a)-(c), the fragment deformation is the smallest in Fig. 19(c) and the largest in Fig. 19(a) in simulation results. In Fig. 19(a), the consistency between experiment and simulation results is the best. In contrast, the consistency in Fig. 19(b) is not good. Via analyzing the differences, it is concluded that the effect of Kevlar in the simulation to transmit shock wave is different from the actual situation. In addition, as the thermal coupling effect is not taken into account in the simulation, the deformation result is not well consistent with the test. Comparing Figs. 19(d)-(f), the fragmentation deformation of Fig. 19(d) is the largest but the smallest in Fig. 19(f). By comparing the section images of spherical fragments and cylindrical fragments, there are a large number of spall fractures in the central part of cylindrical fragments. The spall fractures are close to the back of the fragments, which is consistent with the experimental results obtained by Anderson et al. [14-17]. It indicates that under the detonation loading condition, the spall damage inside the material cannot be avoided by lining, but the damage degree changes.

5. Conclusion

In this paper, two lining materials were used to investigate the dynamic response process of the fragments under detonation loading. The deformation patterns of the fragments were observed and analyzed by SEM and EBSD, and the deformation mechanism of the fragments was revealed. Through the above analysis, the following conclusions could be drawn:

1) The deformation process of the fragments under detonation loading is very rapid, completed within $10\text{-}20 \mu\text{s}$. It is found that the lining cannot change the deformation mode of the fragment, but the deformation degree can be adjusted. The reason is that the existence of lining can only slightly adjust the detonation wave so that its shape and pressure change.

2) The Kevlar/epoxy lining material is beneficial to reduce the fragments deformation degree, preserving the initial velocity of fragments and maintaining the fragments quality integrity. In fact, the lining materials play an adjust role in propagation of shock wave, includes the pressure value and direction of shockwave. It is observed that the effect of lining materials on shockwave is more significant on pressure, compared to the wave direction. The composite of Kevlar and epoxy retains the high tenacity of Kevlar fiber, which can which can effectively reduce the pressure applied on the fragment material.

3) Compared with cylindrical fragments, spherical fragments have better adaptability to the wave-front shape of shock wave. When the spherical surface of fragments suffers from the impact of shockwave, although the peak pressure is same with cylindrical fragments, the average pressure is lower. Their deformation and mass loss are smaller.

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Nomenclature

M_{a3}	: The Mach number in the region (3)
M_{a1}	: The Mach number in the region (1)
k	: The adiabatic index of detonation product
k_0	: Is a part, which is related to density, of k
ρ_0	: The density of the mixed explosive (g/cm^3)
μ_i	: The mass percentage of component i of mixed explosive
M_i	: The molar mass of component i of mixed explosive
k_{0i}	: k_0 of component i of the mixed explosive
ρ_{m0}	: The initial density of the lining
a, b	: The empirical constants of impact compression of lining
D_c	: Explosive detonation velocity
θ	: Flow deflection angle
ρ_m	: The density of the medium after the wave
p_m	: The pressure of the medium after the wave
u_m	: The particle velocity of the medium after the wave
D_m	: The transmitted wave velocity
$\sqrt{2E}$	: Gurney characteristic velocity
C	: The masses of explosive
M	: The masses of fragments
L	: The height of the charge
D	: The diameter of the charge
r	: The radial distance between a fragment center with charge's axle wire
r_{max}	: The charge's radius, $r_{max} = D/2$
$V_M = V_c$	: The maximum initial velocity of the central fragment

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