Effects of shell thickness on the fragment velocity distribution of D-shaped casing filled with explosive

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Abstract. Asymmetric casings filled with explosive have attracted increasing attention in the defence technology (e.g. innovative warhead design) and improvised explosive devices (IEDs) protection. As a typical asymmetric casing, D-shaped casing has been used in deformable aimable warhead, deployable aimable warhead as well as warhead in hypersonic weapons. To assist the design of asymmetric warhead, this work examined the velocity distribution of fragments from the bottom part of the D-shaped casing with different shell thickness. The fragment velocity distributions of the D-shaped casings with different shell thickness were numerically analyzed based on the SPH method. Numerical and theoretical analysis showed that there are opportunities to do optimization of shell thickness of D-shaped casings to maximum the utilization of the energy released by explosive. The findings herein could serve as a reference for further investigations on the fragment velocity distribution of D-shaped casings and provide a foundation for asymmetric warhead design.

1. Introduction

In the design of conventional fragment warheads, the charged casings are commonly in an axially symmetric shape and the detonation point is commonly set on the axis. After the initiation of the explosive charged in the casing, the shell of the casing will be broken into numerous fragments that have approximately equal velocity, shape and mass in all radial directions. Nevertheless, in the most recent applications of the casings filled with explosive such as intelligent warhead design, the explosive charge may be not initiated on the axis and even the casing itself may not be axially symmetric at all.

Compared to the conventional symmetric casings, the explosive loading on the shell of the asymmetric ones is not equal in different radial directions, the circumferential mass and velocity distributions of fragments are thus not uniform. In addition, the designed warheads can make fragments to converge or disperse after initiation [1]. For the development of the innovative warheads, it is essential to conduct the relative studies on the fragments distribution of asymmetric casing under internal explosive loading and its optimization methods.

Recently, there are a number of studies on fragmentation process and the velocity distribution of symmetric casings filled with explosive in the field of defence technology and protection engineering, and the corresponding calculating methods are mature. For example, Guangyan Huang have studied the velocity axial and circumferential distribution of fragments of finite-length cylindrical casings on
the basis of results from the X-ray radiograph technique [2-3], which provides a solid foundation for subsequent experimental and numerical studies. Mafa Wang proposed an empirical model to calculate the fragment velocity circumferential distribution of symmetric casings under eccentric initiation [4]. According to the analytical and numerical methods, Yuan Li did further research on the velocity distribution of axial symmetric casings and established an empirical analysis method to calculate the distribution of fragment velocity distribution [5]. Furthermore, DHOTE experimentally studied the fragments distribution of a type of axial-enhancement warhead [6], which laid the groundwork for tailoring the fragment profile of aimable warhead.

In our previous study on the asymmetry casing filled with explosive, the fragmentation and fragment velocity distribution of a type of D-shaped casing had been tested and analyzed by means of X-ray radiograph technique [7]. But there is merely few studies on the effects of shell thickness of D-shaped casing on the fragment velocity distribution, which is very important for the design of innovative warheads. Therefore, in this study, the effects of shell thickness of D-shaped casing was numerically studied by using AUTODYN. A series of 2D numerical models had been proposed and the fragment velocity distribution of D-shaped casing with different shell thickness was then analyzed.

2. Numerical model establishment

The fragmentation of casing under internal explosive loading is closely related to ultra-high velocities, extreme strains and fractures. The extreme deformation of the casing shell, the expansion of the explosive product and inaccurate failure model make it difficult to do numerical simulation with conventional finite element methods (FEM). However, the smoothed particle hydrodynamics (SPH) method, which is a meshless simulation method, can overcome the limitations of FEM. Therefore, in this study, the fragmentation and fragment velocity distribution of D-shaped casing would be simulated by SPH method.

Figure 1 shows the cross-section of the D-shaped casing overlaid with schematic illustration in our previous research [7]. The shell of the D-shaped casing can be divided into two parts: arc part and bottom part. In the application of the D-shaped casings, the bottom part is used to generate the fragment cluster aiming to the target, so the emphasis of this paper is on the fragment velocity distribution of the bottom part.

In the figure 1, O is the center of the casing, \( r \) is the radius of the explosive, A is the detonation point and \( e_i \cdot r \) is the distance between the detonation point and the center. The fragments in the bottom part can be represented by point Q and described by the relative position factor \( x_i r \), which varies from -1 to 1.

![Figure 1. Photo and schematic diagram of the D-shaped casing [7]](image)

2.1. Structure parameters

There are a plenty of studies on the fragmentation of casings under internal explosive loading and the numerical model can be set on the basis of existing research. In our previous experimental research on the fragment velocity distribution of D-shaped casings [7], the D-shaped casings were made of AISI
1045 and the explosive charged in the casing is Composition B. In the existing studies, the radius of explosive was set as 20mm and the shell thickness was 2mm. In this paper, the influence of arc part shell thickness will be studied, thus the shell thickness of the bottom part is set as constant with value of 2mm, and that of the arc part will vary from 0 to 8mm. The structure parameters of D-shaped casings are shown in table 1, which are designed based on the existing studies. In addition, the eccentric ratio of D-shaped casings was set as a constant value of 1, which means the eccentric initiation effects are not considered in this paper. The representative numerical model, whose parameters are the same as that of the middle section of the in the previous research [7] is shown in figure 2.

| Table 1. Structure parameters of D-shaped casings |
| --- | --- | --- |
| Radius of explosive | Thickness of the arc part | Thickness of the bottom part |
| $r$/mm | $h_a$/mm | $h_b$/mm |
| 0 | 0 | 2 |
| 0.5 | 1 | 2 |
| 20 | 2 | 2 |
| 1 | 4 |
| 2 | 8 |

Figure 2. Representative numerical model of the D-shaped casing

2.2. Material models
For the consistence among this study and previous research, the materials in the numerical model are the same as that from the previous research [7, 8], which means the shell is set as AISI 1045 and explosive is set as Composition B.

AISI 1045 is a common used steel in the engineering and its dynamic mechanical property can be described by Johnson-Cook (J-C) constitutive model. The J-C constitutive model can be expressed as:

$$\sigma = (A + B\varepsilon^p)(1 + C \ln \dot{\varepsilon}^p)(1 - T^\gamma),$$

where $A$ is the yield strength, $B$ is the strain strengthening coefficient, $C$ is the strain rate strengthening coefficient, $m$ and $n$ are soften exponent and strain strengthening exponents, $\varepsilon^p$ is equivalent plastic strain, $\dot{\varepsilon}^p$ is the relative plastic strain rate. The $T^\gamma$ is the homologous temperature, which can be
expressed as \( T^* = \frac{(T-T_r)}{(T_m-T_r)} \), where \( T_r \) is the room temperature, \( T_m \) is the melting temperature. In this paper, the influences of temperature were neglected.

The fracture of the shell of casing were simulated based on the plastic strain failure criterion. In order to simulate the fragmentation process of the cylindrical casing accurately, the Mott stochastic failure model [8] was also utilized, which can be expressed as:

\[
dp = (1-P)Ce^\gamma de ,
\]

(2)

where \((1-P)\) is the probability that there is no fracture for the strain less than \( e \). According to Mott’s theory, \( \gamma \) can be expressed as:

\[
\gamma = 160\frac{\sigma_f}{\sigma_f(1+\varepsilon_f)} ,
\]

(3)

where \( \sigma_f \) is the true stress at the fracture while \( \varepsilon_f \) is the true strain, and \( \sigma_2 \) is the enhancement coefficient of the strength. According to the numerical study of Wei Li [8], \( \gamma \) and \( \varepsilon_f \) are set as 53.8 and 0.65 respectively. The material model parameters of the shell are listed in table 2.

### Table 2. The parameters of the model of shell

| Material       | \( A \) /MPa | \( B \) /MPa | \( C \) | \( m \) | \( n \) | \( T_m/K \) | \( \gamma \) |
|----------------|-------------|-------------|------|------|------|-------------|--------|
| AISI 1045      | 507         | 320         | 0.28 | 0.064| 1.06 | 1793        | 0.23   |

The physical characteristics of explosive products of the Composition B after initiation could be described by JWL equation of state. JWL model is the most common model in the research on explosively driving, propagation of detonation wave and performance of explosives. It can be expressed as:

\[
P_e = C_1(1-\frac{\omega}{R_1V})e^{-\frac{E}{R_1V}} + C_2(1-\frac{\omega}{R_2V})e^{-\frac{E}{R_2V}} + \frac{\omega E}{V} ,
\]

(4)

where \( P_e \) is the pressure of the explosive products, \( E \) is the internal energy per initial volume, \( V \) is the initial relative volume, \( C_1, C_2, R_1, R_2, \omega \) are constant material parameters. The parameters of the JWL model are listed in table 3 [8].

### Table 3. The parameters of the model of explosive

| Material  | \( \rho_0 \) /g·cm\(^{-3}\) | \( D \) /m·s\(^{-1}\) | \( P_{Cl} \) /GPa | \( E_0 \) /KJ·m\(^{-3}\) | \( C_1 \) /GPa | \( C_2 \) /GPa | \( R_1 \) | \( R_2 \) | \( \omega \) |
|-----------|-------------------------|-----------------|-----------------|---------------------|---------------|---------------|------|------|------|
| Comp. B   | 1.717                   | 7980            | 29              | 8.5×10\(^5\)       | 542           | 7.68          | 4.2  | 1.1  | 0.24 |

Furthermore, according to the existing numerical studies on the fragmentation of charged casings [8, 9], it is considered that the SPH simulating model was accurate enough to simulate the eccentric initiation effects, axial rarefaction waves effects and the propagation of detonation waves in D-shaped casings when the particle radius is smaller than 0.4 mm. To minimize the calculation cost with enough numerical accuracy, the particle radius was set to 0.4 mm in the most parts of model. But the particle radius of the arc part shell was fitted to the arc part shell thickness, which means the particle radius vary from 0.05 to 0.4.

3. Numerical results analysis

Based on the numerical model, the fragmentation of D-shaped casings with different shell thickness can be obtained. The analysis on the numerical results focuses on the fragment velocity distribution and kinetic energy distribution.

3.1. Fragment velocity distribution

At first, based on the information from the gauges, the fragment velocity distribution can be obtained. Due to the symmetry of the D-shaped casing, we only considered the fragment with \( x \), from 0 to 1, that is, we considered the fragment velocity in the right half of the casing.
Figure 3 shows the fragment velocity distribution of the bottom part of the D-shaped casings with different arc part shell thickness. It can be observed that velocity of the fragments near to the edge \((x_r>0.7)\) is lower than that of other fragments. And it can be found if there is no arc part shell \((h_a=0)\), the fragment velocity of the bottom part will be obviously lower than that in other D-shaped casings. When \(h_a\) become 0.5mm or 1mm, the fragment velocities generally increase especially the fragment near to the edge. The reason is that the shell can suppress the expansion of the explosive products and improve the fragment velocity in the bottom part. With the increase of arc part shell thickness, velocity of the fragments near to the edge will further increase while that of others only increase a little. Therefore, it can be obtained that the arc part shell plays an important role in suppressing the expansion of explosive and optimizing the D-shaped casing shell thickness.

![Figure 3. The fragment velocity distribution of the bottom part](image)

It is essential to consider the velocity of the fragments near to the center \((x_r=0)\) of the D-shaped casings because the central fragment velocity is a foundation for the warhead optimization. Figure 4 shows the relationship between arc part shell thickness and central fragment velocity. It can be found that, with the increase of the arc part shell thickness, the central fragment velocity increases significantly at first and then decreases a little. After the slight decline, the central fragment velocity will still increase with shell thickness of arc part. It can be concluded that when the shell thickness of the arc part is small, there will be an optimal thickness, which can be a reference for warhead design.
3.2. **Kinetic energy analysis**

Fragment kinetic energy distribution is also an important factor because it represents the energy output characteristics of D-shaped casing. Therefore, a factor called kinetic energy proportion has been proposed and denoted as $\eta$, which can be expressed as:

$$\eta = \frac{E_k}{E_{ex}}.$$  \hspace{1cm} (5)

Where $E_k$ is the total kinetic energy of arc part, bottom part or explosive products, $E_{ex}$ is the total energy of explosive before initiation. The proposed factor can be used to characterize the energy output structure of explosive because the mass of explosive remains constant in this study.

Based on the numerical results and definition of the kinetic energy proportion, the kinetic energy proportion of the arc part and the bottom part of D-shaped casings with different shell thickness can be obtained respectively and shown in figure 5. It can be observed that, with the increase of the arc part shell thickness, the kinetic energy in the arc part increases sharply until $h_a=2$ and then slightly declines, while that in the bottom part will firstly increase obviously and then slowly increase after a slight drop. Combined with the conclusions in the section 3.1, it can be concluded that, in the D-shaped warhead design, a thin arc part shell can effectively suppress the explosive energy waste. And the thick arc part shell design may not be suitable because it leads to an obviously increase of useless quality with only a slight improvement of the energy in the bottom part.
4. Conclusion

In conclusion, the velocity distribution of the fragments in the bottom part of the D-shaped casings with different shell thickness has been investigated numerically. The effect of the arc part shell thickness on the fragment velocity distribution of the bottom part and the kinetic energy proportion of two parts have been obtained in this study. The following conclusions can be drawn from this study:

(1) A series of numerical models were established to study the influence of shell thickness on the fragment velocity distribution. The numerical model was established on the basis of SPH method, which is suitable to simulate the fragmentation of the casings. The fragment velocity of bottom part and kinetic energy proportion distribution were then obtained.

(2) According to the fragment velocity distribution of the bottom part, it can be concluded that the arc part shell has a significant influence on the fragment velocity distribution of the bottom part by suppressing the explosive products expansion. And the thicker arc part shell can obviously suppress the explosive products expansion in the region near to the edges of the casing, which is more severe than that near to the center.

(3) The kinetic energy proportion was proposed to analyze the effect of shell thickness on the distribution of energy from explosive. It was found that when the shell thickness was larger than 1mm, the kinetic energy in the bottom part would only increase slowly. And thin arc part shell design is relatively better in the D-shaped warhead design. The corresponding conclusions can be a reference for further optimization of D-shaped casing.

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