Numerical Simulation of Rod Jet Formed by Shaped Charge under Rigid Constraint

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Abstract. In order to study the forming law of rod jet formed by shaped charge under rigid boundary constraint, ANSYS/LSDYNA finite element software is used to simulate the forming process of rod jet with ALE essential boundary, and the influence of structural parameters of shaped charge on rod jet forming is studied. The results show that compared with the free boundary constraint, the head velocity of rod jet increases by 63.5% and the tail velocity increases by 59.3% under the rigid boundary constraint. The head velocity and length-diameter ratio of rod jet decrease with the increase of the outside curvature radius of the liner, the thickness of the liner central position and the variable ratio of wall thickness. Furthermore, the tail velocity increases with the increase of the outside curvature radius of the liner, and decreases with the increase of the thickness of the liner central position and the variable ratio of wall thickness.

1. Introduction
As a common warhead, shaped charge mainly uses the Munro effect to convert the explosive internal energy into the kinetic energy of rod jet. In the detonation process of explosives, only partial energy converges, and the remaining energy dissipates circumferentially with the detonation products as the carrier. In order to improve the head and tail velocity of rod jet, shell can be added around the shaped charge, which can delay and even avoid the entry of rarefaction waves, which improve the utilization rate of explosive energy. Brow[1] studied the influence of shell shape on the transverse velocity of shaped charge jet by means of high-speed camera technology. Gao[2,3] studied the influence of shell on the jet by means of theoretical and experimental. Liu[4] analysed the influence of shell material and shell thickness on jet velocity with numerical simulation. Tang[5] studied the influence of shell structure and shell thickness on explosively formed projectile with tail wing. Wu[6] studied the influence of shell thickness on forming parameters such as velocity and length-diameter ratio of rod jet. In some special applications of the shaped charge, there is no need to produce fragmentation and dispersion in the circumferential direction of the charge. The current research is mostly aimed at the influence of the shell with a certain thickness and strength on the forming performance of rod jet. However, the influence of the limit shell thickness, especially the strength of the limit shell, on rod jet forming is rarely considered. In this paper, based on the typical shaped charge structure with variable ratio of wall thickness spherical liner, the influence of structural parameters of shaped charge on rod jet forming under strong constraint is studied by using ANSYS/LSDYNA finite element software.
2. Numerical Calculation Model

2.1. Structure of Shaped Charge

Figure 1 shows the geometric model diagram of shaped charge structure. The structure is composed of explosive and liner. The bottom diameter of the charge is $D_1$, length is $L$, charge bottom angle is $\theta$; the outside curvature radius of the liner is $R$, the thickness of the liner central position is $\delta$, and the bottom thickness of the liner is $\delta_1$, the ratio of thickness of the liner bottom position $\delta_1$ to the central position thickness of the liner $\delta$, is defined as the variable ratio of wall thickness, which is expressed as $\varepsilon = \delta_1 / \delta$.

Figure 1. Geometric model diagram of shaped charge which composed of explosive and liner

2.2. Finite Element Model

LSDYNA finite element analysis software and ALE algorithm are used to calculate rod jet forming process. Due to the symmetry of the charge structure, a quarter three-dimensional model is established for calculation. The rigid boundary constraint is simulated by fixing charge boundary conditions, and controlled by the keyword *ALE_ESSENTIAL_ BOUNDARY. The keyword simplifies the outer area of the charge to ‘pipeline’, so that explosive and detonation products can flow in it, without damaging the ‘pipeline’. The air domain boundary is controlled by the*BOUNDARY_NON_ REFLECTING keyword with no reflection boundary condition, and the different boundary condition regions are shown in Figure 2. Figure 3 shows the finite element calculation model. Considering the sensitivity of the calculation results to the grid size and the calculation efficiency, it is determined that the grid unilateral size is 0.5 mm, and the unit system adopts cm-g-µs.

Figure 2. Diagram of different boundary conditions.  
Figure 3. Finite element calculation model.

2.3. Material Model

JH-2 is used as the explosive, and JWL model is selected as the equation of state. The model can well show the relationship between energy, pressure and volume of detonation products. The general pressure form[7] is:

$$P = A(1 - \frac{\omega}{R_1 V})e^{-R_1 V} + B(R_2 V)e^{-(R_2 V)} + \frac{\omega E}{V}$$

(1)

In the equation, $E = \rho_0 e$ is the internal energy per unit initial volume. $A, B, R_1, R_2, \omega$ are constants determined by experiments. The JWL model parameters of explosive materials are shown in Table 1.
The liner uses copper material using Johnson-Cook strength model and Grüneisen equation of state. Johnson-Cook strength model can simulate the dynamic behavior of materials under large strain and high strain rate. Its mathematical expression is:

\[ \sigma_T = (A + B\epsilon_n^m)(1 + C \ln \dot{\epsilon}^\ast)(1 - T^\ast) \] (2)

where

\[ T^\ast = (T - T_r) / (T_m - T_r) \] (3)

In the equation (2), \( \epsilon \) is effective plastic strain. \( \dot{\epsilon}^\ast = \dot{\epsilon} / \dot{\epsilon}_0 \) is the dimensionless strain rate, and \( T^\ast \) is the melting point of the material. \( A, B, n, C, m \) are the material parameters. \( T_r \) is the similar temperature. The Johnson-Cook constitutive equation parameters of liner material are shown in Table 2.

### Table 1. JWL model parameters of JH-2[8].

| \( \rho / (\text{g/m}^3) \) | D$_0$ / GPa | p$_C$ / GPa | A$_1$ / GPa | B$_1$ / GPa | R$_1$ | R$_2$ | \( \omega \) | E / GPa |
|---|---|---|---|---|---|---|---|---|
| 1.70 | 8315 | 29.5 | 854.5 | 20.49 | 4.60 | 1.36 | 0.25 | 8.5 |

### Table 2. Johnson-Cook constitutive equation parameters[9].

| \( \rho / (\text{g/m}^3) \) | A / GPa | B / GPa | n | C | m | T$_m$ / K |
|---|---|---|---|---|---|---|
| 8.96 | 0.09 | 0.292 | 0.31 | 0.025 | 1.09 | 1356 |

### 3. Numerical Calculation Results and Analysis

#### 3.1. Analysis of Rod Jet Forming Process under Rigid Boundary Constraint

In order to study the forming process of rod jet under rigid boundary constraint, the free boundary constraint is compared with rigid boundary constraint under the same charge structure.

![Figure 4](image)

Figure 4. Detonation pressure nephogram of charge under different boundary conditions.

Figure 4 is the detonation pressure nephogram of charge at different times under rigid boundary constraint. It can be seen from Figure 4 that at the beginning of the detonation, the detonation wave propagates forward in the form of spherical wave. Compared with the free boundary constraint, the entrance of rarefaction wave is reduced. In addition, the total reflection between the detonation wave and the boundary change the waveform of the detonation wave’s tail. At 6\( \mu \)s, the wave front reaches the liner and produces reflection at the central axis. At 8\( \mu \)s the peak area of the detonation wave is...
approximately conical and the maximum pressure shows at the bottom of the liner. The whole detonation wave pressure decays slowly during explosive detonation.

Table 3 shows the forming parameters of rod jet at 60 μs under different constraints. It can be seen from the table that under rigid boundary constraint, the head velocity of rod jet increases by 63.5 %, the tail velocity increases by 59.3 %, and the overall kinetic energy increases by 123.2 %. It can be seen from the calculation results that compared with the free boundary condition, the rigid boundary constraint can effectively increase the velocity of rod jet and improve the energy utilization rate of explosive.

Table 3. Rodjetmolding parameter at 60μs under different boundary constraints.

| Boundary | Result | Head speed (m/s) | Tail Speed (m/s) | Length (mm) | Length diameter ratio | Kinetic energy (KJ) |
|----------|--------|-----------------|-----------------|-------------|----------------------|--------------------|
| Free     | 3200.0 | 1787.0          | 74.0            | 10.2        | 97                   |
| Rigid    | 5233.0 | 2846.0          | 126.4           | 21.1        | 220                  |

3.2. Influence of Charge Structure Parameters on Rod Jet Forming

In view of the above model, the control variable method is used to study the influence of structural parameters of shaped charge on rod jet forming under rigid boundary constraint. Head velocity \(v_h\), tail velocity \(v_t\), length \(l\), length-to-diameter ratio \(l/d\) of rod jet are selected as the evaluation indexes.

3.2.1. Effect of Charge Length on Rod Jet Forming

The charge structures of \(D=56\text{mm}, D_0=D, \theta=0^\circ, R = 0.7143 \ D, \delta = 0.0445 \ D, \varepsilon = 0.8\) are selected. The increment of \(L\) in the range of \((0.8035\sim1.1607)D\), increment step is 0.0893D, and the forming law of shaped charge jet is calculated.

![Figure 5. Variation of rod jet velocity of rod jet with length-diameter ratio of charge.](image1)

![Figure 6. Variation of rod jet length and length-diameter ratio of rod jet with length-diameter ratio of charge.](image2)

It can be seen from Figure 5 and Figure 6 that the head velocity and tail velocity of rod jet show an increasing trend with the increase of charge height. The head velocity increases by about 17.2 %, the tail velocity increases by about 8.9 % and the head velocity increases faster than the tail velocity. The length and length-diameter ratio of rod jet also show an increasing trend with the increase of charge length, the length increased by about 21.8 %, and the length-diameter ratio increased by about 42.1 %.

3.2.2. Effect of the Charge Bottom Angel on Rod Jet Forming

The charge structures of \(D=56\text{mm}, D_0 = 0.5357D, L=1.0714D, R = 0.7143 \ D, \delta = 0.0445 \ D, \varepsilon = 0.8\) are selected. The increment of \(\theta\) in the range of \((30^\circ \sim 70^\circ)\), increment step is 10°, and the forming law of shaped charge jet is calculated.
It can be seen from Figure 7 and Figure 8 that with the increase of the charge bottom angle, the head velocity of rod jet has a decreasing trend and the tail velocity has an increasing trend, but the variation is small. The length and length-diameter ratio have a decreasing trend, the length decreases about 3.6 %, the length-diameter ratio decreases about 24.3 %.

3.3. The Influence of Liner Structure Parameters on Rod Jet Forming

3.3.1. Effect of Outside Curvature Radius of the Liner on Rod Jet Forming

The charge structures of $D=56\,\text{mm}$, $D_1 = 0.5357D$, $\theta=60^\circ$, $L=1.0714D$, $\delta = 0.0445 \, D$, $\epsilon = 0.8$ are selected. The increment of $R$ in the range of $(0.5357 \sim 0.8929)D$, increment step is $0.0893D$, and the forming law of shaped charge jet is calculated.

It can be seen from Figure 9 and Figure 10 that with the change of the outside curvature radius of the liner, in the range of $(0.5357 \sim 0.8929)D$, the head velocity of rod jet shows a decreasing trend, while the tail velocity shows an increasing trend. The head velocity decreases by about 80.0 %, and the tail velocity increases by about 49.6 %. The length and length-diameter ratio of rod jet show a decreasing trend. The length decreases by about 326.9 %, and the length-diameter ratio decreases by about 160.7 %. The morphology of the penetrator gradually changes from the jet to Explosively Formed Projectile (EFP).
3.3.2. Effect of Top Thickness of Liner on Rod Jet Forming
The charge structures of \( D=56 \text{mm}, D_1 = 0.5357D, L=1.0714D, \theta =30^\circ, R = 0.7143 \text{ } D, \varepsilon = 0.8 \) are selected. The increment of \( \delta \) in the range of \((0.0312 \sim 0.0491) \text{ } D \), increment step is 0.0045D, and the forming law of shaped charge jet is calculated.

![Figure 11. Variation of rod jet velocity with the thickness of the liner central position.](image1)

![Figure 12. Variation of length and length-diameter ratio of rod jet with the thickness of the liner central position.](image2)

It can be seen from Figure 11 and Figure 12 that with the increase of the thickness of the liner central position, in the range of \((0.0312 \sim 0.0491)D \), the head velocity and tail velocity of the rod jet show a decreasing trend. The head velocity decreases by about 21.8 \%, and the tail velocity decreases by about 16.4 \%. The length and length-diameter ratio of rod jet show a decreasing trend, the length decreased by about 22.6 \%, and the length-diameter ratio decreased by about 71.6 \%, but the decreasing trend of length is gradually gentle.

3.3.3. Effect of Variable Wall Thickness Ratio of Liner on Rod Jet Forming
The charge structures of \( D=56 \text{mm}, D_1 = 0.5357D, L=1.0714D, \theta =30^\circ, R = 0.7143 \text{ } D, \delta = 0.0446D \) are selected. The increment of \( \varepsilon \) in the range of \((0.8 \sim 1.2)\), increment step is 0.1, and the forming law of shaped charge jet is calculated.

![Figure 13. Variation of rod jet velocity with variable wall thickness ratio of liner.](image3)

![Figure 14. Variation of length and length-diameter ratio of rod jet with variable wall thickness ratio of liner.](image4)

From Figure 13 and Figure 14, it can be seen that with the increase of liner thickness change rate, in the range of \( 0.8 \sim 1.2 \), the head and tail velocity of rod jet both show a decreasing trend, the head velocity decreases by about 7.8 \%, and the tail velocity decreases by about 10.4\%. The length and
length-diameter ratio of rod jet show a decreasing trend. The length decreases by about 3.4 % and the length-diameter ratio decreases by about 6.9 %, but the decreasing trend of length is gradually flat.

4. Conclusion
The numerical simulation method is used to conduct a comparative study of the rod jet forming process under the free boundary constraint and the rigid boundary constraint, and the influence of the structural parameters of shaped charge on rod jet forming law under the rigid boundary constraint is studied. The specific conclusions are as follows:

1) Under the rigid boundary constraint, compared with the free boundary condition, the head velocity of rod jet increases by 63.5 %, the tail velocity increases by 59.3 %, and the overall kinetic energy increases by 123.2 %.

2) Under the rigid boundary constraint, with the increase of the charge length, the head and tail velocity of rod jet increases, and rod jet has a gradually elongated trend. The change of the charge bottom angle has little effect on the velocity and morphology of rod jet.

3) Under the rigid boundary constraint, the velocity, length and length-diameter ratio of rod jet decrease with the increase of the outside curvature radius of the liner, the liner central position thickness and the variable ratio of wall thickness. The tail velocity increases with the increase of outside curvature radius of liner, and decreases with the increase of the thickness of liner central position and variable ratio of wall thickness.

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