Forming Control of Rod-Shaped Tantalum-Tungsten Alloy Explosively Formed Projectile

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Abstract. In order to obtain the charge structure of rod-shaped tantalum-tungsten alloy (Ta-W) explosively formed projectile (EFP) with good performance indicators, the LS-DYNA numerical simulation software was used to study the arc-cone liner different charge structure parameters (such as curvature radius, half cone angle and thickness of liner, charge height and shell thickness) on the forming of Ta-W EFP so that the optimal range of each structural parameter was determined. The primary and secondary order of the influence of various structural parameters on the forming performance of Ta-W EFP was obtained by orthogonal optimization design, and the optimized plan of rod-shaped Ta-W EFP was determined (curvature radius of liner is 1.16071D, half cone angle of liner is 68.5°, thickness of liner is 0.02054D, charge height is 0.85714D and shell thickness is 0.08929D, where D is charge diameter). The results show that the performance indicators of the optimized plan of rod-shaped Ta-W EFP are better, whose velocity is 2312m/s, length-to-diameter ratio is 4.41998, compactness is 0.95929 and necking ratio is 0.21109.

1. Introduction

Explosively formed projectile (EFP) is a kind of high-velocity projectile with good aerodynamic shape formed by the principle of gathering energy which can effectively damage armored targets at large explosive heights which is widely used in intelligent and smart ammunition such as terminal sensitive projectiles[1-2]. At present, scholars have conducted a lot of research on the commonly used copper EFP and its penetration ability has reached its limit. Therefore, tantalum and its alloys have the characteristics of high density, high melting point and high ductility that gradually become a hot spot for new materials of liner. Fan Xuefei[3] obtained Johnson-Cook constitutive model of tantalum material through Hopkinson experiment and conducted a lot of numerical simulation studies. Zhu Zhipeng[4] studied the influence of large aspect ratio tantalum EFP forming but did not add the failure model that is impossible to simulate the real tensile situation. Men Jianbing[5] obtained the Johnson-Cook failure model of Ta-W through the tests of the mechanical properties, however, the forming law of Ta-W EFP has not been studied.

In this paper, the LS-DYNA numerical simulation software is used to study the arc-cone liner different charge structure parameters (such as curvature radius, half cone angle and thickness of liner, charge height and shell thickness) on the forming of Ta-W EFP. The primary and secondary order of the influence of various structural parameters on the forming performance of Ta-W EFP was obtained by orthogonal optimization design, and the optimized EFP charge structure parameter combination was determined.
2. Simulation Model and Material Model

2.1. Geometric Model and Calculation Method

The charge structure consists of shell, charge, and arc-cone liner, where D is charge diameter, L is charge height and h is shell thickness, as shown in Figure 1. The liner adopts an arc-cone structure with equal thickness, where R is curvature radius, α is half cone angle and δ is thickness of liner.

The LS-DYNA numerical simulation software is used to simulate the forming process of Ta-W EFP. The calculation method adopts the Lagrange algorithm and half of two-dimensional model is established because of the symmetry of the structure. The system of unit adopts cm-g-us and each part is divided by No.14 Shell element. Add the keyword *CONTROL_ADAPTIVE to divide the structure of liner. The grid division size is selected to be 0.7mm in order to improve the efficiency and the accuracy of the calculation, however, the number of grids in the thickness direction of liner is fixed to 4 because the thickness of liner is too thin, as shown in Figure 2.

2.2. Material Model and Parameters

The explosive is JH-2 with JWL model whose parameters are shown in Table 1. The shell is 45 steel with Johnson-Cook constitutive model whose parameters are shown in Table 2. The liner is Ta-W with Johnson-Cook constitutive model and Johnson-Cook failure model whose parameters are shown in Table 3.

| Table 1. Material parameters of JWL model for JH-2 explosive[^6]. |
|---|---|---|---|---|---|---|
| ρ/(g·cm⁻³) | D₀/(m·s⁻¹) | p_c/GPa | A₀/GPa | B₀/GPa | R₁ | R₂ | ω | E/GPa |
| 1.70 | 8315 | 29.50 | 854.5 | 20.49 | 4.60 | 1.35 | 0.25 | 8.5 |

| Table 2. Material parameters of Johnson-Cook constitutive model for 45 steel shell[^7]. |
|---|---|---|---|---|---|
| ρ₁/(g·cm⁻³) | A/MPa | B/MPa | n | C | m | Tₘ/K | Tᵣ/K |
| 7.89 | 506 | 320 | 0.28 | 0.0084 | 1.06 | 1795 | 294 |

| Table 3. Material parameters of Johnson-Cook failure model for Ta-W liner[^5]. |
|---|---|---|---|---|---|
| ρ₂/(g·cm⁻³) | D₁ | D₂ | D₃ | D₄ | D₅ |
| 16.65 | 1.355 | 1.833 | -1.930 | 0.015 | 1.868 |

3. Influence of Structural Parameters on EFP

Control variate is used to study the arc-cone liner different charge structure parameters (such as curvature radius, half cone angle and thickness of liner, charge height and shell thickness) on the forming of Ta-W EFP. Figure 3 defines the feature parameters of EFP for ease of description and analysis, where l is the length of EFP, d is the diameter of EFP, l₁ is the length of EFP compact section, and d₁ is the minimum diameter of EFP. Defining compactness P=l₁/l, the greater the compactness, the better the penetration ability of EFP; necking ratio Q=(d-d₁)/d, the greater the necking ratio, the more likely the EFP fractures.
3.1. Influence of Curvature Radius of Liner on EFP

So as to study the influence of curvature radius of liner on EFP, calculate the forming process of EFP when curvature radius $R$ of liner is $0.83928D$~$1.28571D$ (increment is $0.08929D$), based on $D=56mm$, $\alpha=68^{\circ}$, $\delta/D=0.02321$, $L/D=0.85714$, $h/D=0.08929$. Figure 4 shows a typical forming process of EFP of arc-cone Ta-W liner. Figure 5 shows forming morphology, velocity $v$, length-to-diameter ratio $l/d$, compactness $P$ and necking ratio $Q$ at $t=240\mu s$ as $R/D$ changes.

![Figure 3. Feature parameters of EFP.](image)

![Figure 4. Typical forming process of EFP.](image)

![Figure 5. Performance indicators as $R/D$ changes.](image)

It can be seen from Figure 5 that as curvature radius $R$ increases, velocity $v$ increases linearly, length-to-diameter ratio $l/d$ decreases exponentially, compactness $P$ first increases and then decreases, necking ratio $Q$ first decreases and then increases. When $R$ is less than $1.1D$, the EFP is a crush type whose flight is unstable because the center of gravity is back, and it is possible to fracture because necking ratio $Q$ is large. When $R$ is more than $1.2D$, the hollow part of EFP is larger and compactness $P$ is smaller so that the penetration ability is poor. At the same time, necking ratio $Q$ begins to increase, which is possible to fracture. Therefore, the optimal range of curvature radius $R$ is $1.1D$~$1.2D$.

3.2. Influence of Half Cone angle of Liner on EFP

So as to study the influence of half cone angle of liner on EFP, calculate the forming process of EFP when half cone angle $\alpha$ of liner is $65^{\circ}$~$80^{\circ}$ (increment is $3^{\circ}$), based on $D=56mm$, $R/D=1.14286$, $\delta/D=0.02321$, $L/D=0.85714$, $h/D=0.08929$. Figure 6 shows forming morphology, velocity $v$, length-to-diameter ratio $l/d$, compactness $P$ and necking ratio $Q$ at $t=240\mu s$ as $\alpha$ changes.

![Figure 6. Performance indicators as $\alpha$ changes.](image)
It can be seen from Figure 6 that as half cone angle $\alpha$ increases, velocity $v$ increases linearly, length-to-diameter ratio $l/d$ decreases linearly, compactness $P$ first increases and then decreases, necking ratio $Q$ first decreases and then increases. When $\alpha$ is less than 65°, liner cannot be modeled. When $\alpha$ is more than 71°, the shape and penetration ability of EFP are poor because the diameter of EFP increases, the tail elongates and compactness $P$ decreases. Therefore, the optimal range of half cone angle $\alpha$ is 65°~71°.

3.3. Influence of Thickness of Liner on EFP

So as to study the influence of thickness of liner on EFP, calculate the forming process of EFP when thickness of liner $\delta$ is 0.01786D~0.03571D (increment is 0.00357D), based on $D=56\text{mm}$, $R/D=1.14286$, $\alpha=68^\circ$, $L/D=0.85714$, $h/D=0.08929$. Figure 7 shows forming morphology, velocity $v$, length-to-diameter ratio $l/d$, compactness $P$ and necking ratio $Q$ at $t=240\mu s$ as $\delta$ changes.

![Figure 7. Performance indicators as $\delta$ changes.](image)

It can be seen from Figure 7 that as thickness of liner $\delta$ increases, velocity $v$ decreases linearly, length-to-diameter ratio $l/d$, compactness $P$ and necking ratio $Q$ decrease exponentially. When $\delta$ is less than 0.02D, EFP fractures. When $\delta$ is more than 0.03D, the penetration ability of EFP is poor because the velocity, length-to-diameter ratio and compactness are smaller. Therefore, the optimal range of thickness $\delta$ is 0.02D~0.03D.

3.4. Influence of Charge Height on EFP

So as to study the influence of charge height on EFP, calculate the forming process of EFP when charge height $L$ is 0.625D~1.07143D (increment is 0.08929D), based on $D=56\text{mm}$, $R/D=1.14286$, $\alpha=68^\circ$, $\delta/D=0.02321$, $h/D=0.08929$. Figure 8 shows forming morphology, velocity $v$, length-to-diameter ratio $l/d$, compactness $P$ and necking ratio $Q$ at $t=240\mu s$ as $L$ changes.

![Figure 8. Performance indicators as $L$ changes.](image)

It can be seen from Figure 8 that as charge height $L$ increases, velocity $v$ and length-to-diameter ratio $l/d$ increase linearly, compactness $P$ and necking ratio $Q$ first decrease and then increase. When $L$ is less than 0.75D, the penetration ability of EFP is poor because the velocity and length-to-diameter ratio are smaller. When $L$ is more than 0.9D, EFP is possible to fracture because necking ratio $Q$ is greater. Therefore, the optimal range of charge height $L$ is 0.75D~0.9D.
3.5. Influence of Shell Thickness on EFP

So as to study the influence of shell thickness on EFP, calculate the forming process of EFP when shell thickness $h$ is $0.03571D - 0.21429D$ (increment is $0.03571D$), based on $D=56mm$, $R/D=1.14286$, $\alpha=68^\circ$, $\delta/D=0.02321$, $L/D=0.85714$. Figure 9 shows forming morphology, velocity $v$, length-to-diameter ratio $l/d$, compactness $P$ and necking ratio $Q$ at $t=240\mu s$ as $h$ changes.

![Figure 9](image)

Figure 9. Performance indicators as $h$ changes.

It can be seen from Figure 9 that as shell thickness $h$ increases, velocity $v$ increases exponentially, length-to-diameter ratio $l/d$ first decreases and then increases and then fluctuates, compactness $P$ first increases and then decreases, necking ratio $Q$ first decreases and then increases. When $h$ is less than $0.07D$, the shape and penetration ability of EFP are poor because velocity and compactness is smaller and necking ratio is greater. When $h$ is more than $0.14D$, EFP is possible to fracture because necking ratio $Q$ is greater. Therefore, the optimal range of shell thickness $h$ is $0.07D - 0.14D$.

4. Orthogonal Optimization Design

Based on the study in Section 3, orthogonal optimization design is carried out with velocity $v$, length-to-diameter ratio $l/d$, compactness $P$ and necking ratio $Q$ as evaluation indicators to get a rod-shaped Ta-W EFP with good performance.

4.1. Orthogonal Design Plan

Curvature radius, half cone angle and thickness of liner, charge height and shell thickness are taken as the five factors of the orthogonal design. Each factor selects four levels from the optimal range in Section 3, as shown in Table 4. The orthogonal design is carried out $L16$, which is a four-level five-factor orthogonal table, and 16 simulation calculation plans are obtained.

| Level | R/D       | $\alpha$(degree) | $\delta/D$   | L/D       | h/D     |
|-------|-----------|------------------|--------------|-----------|---------|
| 1     | 1.10714   | 65.5             | 0.02054      | 0.78571   | 0.07143 |
| 2     | 1.13393   | 67               | 0.02321      | 0.82143   | 0.08929 |
| 3     | 1.16071   | 68.5             | 0.02589      | 0.85714   | 0.10714 |
| 4     | 1.1875    | 70               | 0.02857      | 0.89286   | 0.125   |

4.2. Results and Analysis

Table 5 shows the results of Ta-W EFP forming at $t=240\mu s$ for the 16 simulation calculation plans in Table 4. In order to get the primary and secondary order of the influence of various structural parameters on the forming performance of Ta-W EFP, use the range analysis method to analyze the calculation results in Table 5 and calculate the range $S$ under each level.
### Table 5. Orthogonal design calculation results.

| Plan | R/D | α   | δ/D | L/D | h/D | v(m/s) | l/d | P    | Q    | The shape of EFP |
|------|-----|-----|-----|-----|-----|--------|-----|------|------|------------------|
| 1    | 1   | 1   | 1   | 1   | 1   | 2194   | 4.81279 | 0.73636 | 0.58527 |
| 2    | 1   | 2   | 2   | 2   | 2   | 2108   | 4.71058 | 0.64532 | 0.50834 |
| 3    | 1   | 3   | 3   | 3   | 3   | 2036   | 3.80178 | 0.86674 | 0.24390 |
| 4    | 1   | 4   | 4   | 4   | 4   | 1976   | 2.23769 | 0.84192 | 0.25436 |
| 5    | 2   | 1   | 2   | 3   | 4   | 2182   | 4.76070 | 0.59215 | 0.56518 |
| 6    | 2   | 2   | 1   | 4   | 3   | 2344   | 5.34609 | 0.65457 | 0.56213 |
| 7    | 2   | 3   | 4   | 1   | 2   | 1855   | 2.47894 | 0.87545 | 0.02961 |
| 8    | 2   | 4   | 3   | 2   | 1   | 1965   | 2.52693 | 0.71667 | 0.16491 |
| 9    | 3   | 1   | 3   | 4   | 2   | 2030   | 3.30819 | 0.85764 | 0.32976 |
| 10   | 3   | 2   | 4   | 3   | 1   | 1853   | 2.59185 | 0.56820 | 0.21902 |
| 11   | 3   | 3   | 1   | 2   | 4   | 2329   | 5.04452 | 0.91154 | 0.48441 |
| 12   | 3   | 4   | 2   | 1   | 3   | 2136   | 2.55030 | 0.93109 | 0.33004 |
| 13   | 4   | 1   | 4   | 2   | 3   | 1909   | 2.51649 | 0.81697 | 0.07861 |
| 14   | 4   | 2   | 3   | 1   | 4   | 2024   | 2.89482 | 0.92528 | 0.25572 |
| 15   | 4   | 3   | 2   | 4   | 1   | 2129   | 3.58436 | 0.53508 | 0.41406 |
| 16   | 4   | 4   | 1   | 3   | 2   | 2316   | 3.46127 | 0.84515 | 0.38189 |

### Table 6. Analysis of orthogonal design of velocity and length-to-diameter ratio.

| Fact | R/D | α   | δ/D | L/D | h/D | v(m/s) | l/d | P    | Q    |
|------|-----|-----|-----|-----|-----|--------|-----|------|------|
| K1   | 2078.50 | 2078.75 | 2295.75 | 2052.25 | 2035.25 | 5.04452 | 0.91154 | 0.48441 |
| K2   | 2086.50 | 2082.25 | 2138.75 | 2077.75 | 2077.25 | 2.55030 | 0.93109 | 0.33004 |
| K3   | 2087.00 | 2087.25 | 2013.75 | 2096.75 | 2106.25 | 2.51649 | 0.81697 | 0.07861 |
| K4   | 2094.50 | 2098.25 | 1898.25 | 2119.75 | 2127.75 | 3.58436 | 0.53508 | 0.41406 |
| S    | 16   | 19.5 | 397.5 | 67.5 | 92.5 | 3.46127 | 0.84515 | 0.38189 |

| Order | δ/D>h/D>L/D>α>R/D | δ/D>α>R/D>L/D|h/D |
|-------|--------------------|--------------------|
| 3.891 | 3.850 | 4.666 | 3.184 | 3.379 |
| 3.778 | 3.886 | 3.901 | 3.700 | 3.490 |
| 3.374 | 3.727 | 3.133 | 3.654 | 3.554 |
| 3.114 | 2.694 | 2.456 | 3.619 | 3.734 |
| 0.777 | 1.192 | 2.210 | 0.516 | 0.355 |
Table 7. Analysis of orthogonal design of compactness and necking ratio.

| Fact-or | Compactness P | Necking ratio Q |
|---------|---------------|-----------------|
|         | R/D | α   | δ/D | L/D | h/D | R/D | α   | δ/D | L/D | h/D |
| K1      | 0.772| 0.751| 0.787| 0.837| 0.639| 0.398| 0.390| 0.503| 0.30 | 0.346 |
| K2      | 0.710| 0.698| 0.676| 0.773| 0.806| 0.330| 0.386| 0.454| 0.30 | 0.312 |
| K3      | 0.817| 0.797| 0.842| 0.718| 0.817| 0.341| 0.293| 0.249| 0.35 | 0.304 |
| K4      | 0.781| 0.834| 0.75 | 0.722| 0.818| 0.283| 0.283| 0.145| 0.39 | 0.390 |
| S       | 0.107| 0.136| 0.166| 0.149| 0.179| 0.115| 0.107| 0.358| 0.09 | 0.086 |

Table 6 is the analysis of orthogonal design of velocity and length-to-diameter ratio. It can be seen that thickness of liner δ is the most important factor affecting velocity v of Ta-W EFP. The primary and secondary order of velocity v is δ, h, L, α, R. Also, thickness of liner δ is the most important factor affecting length-to-diameter ratio l/d of Ta-W EFP. The primary and secondary order of length-to-diameter ratio l/d is δ, α, R, L, h. Likewise, Table 7 is the analysis of orthogonal design of compactness and necking ratio. It can be seen that shell thickness h is the most important factor affecting compactness P of Ta-W EFP. The primary and secondary order of compactness P is h, δ, L, α, R. Thickness of liner δ is the most important factor affecting necking ratio Q of Ta-W EFP. The primary and secondary order of necking ratio Q is δ, R, α, L, h.

4.3. Optimized Plan

According to the orthogonal optimization results in Table 4 and the primary and secondary order of the influencing factors in Table 5 and Table 6, considering the four performance indicators of Ta-W EFP velocity v, length-to-diameter ratio l/d, compactness P and necking ratio Q, the structural parameters of the optimized plan of rod-shaped Ta-W EFP are determined as follows: curvature radius R=1.16071D, half cone angle α=68.5°, thickness δ=0.02054D, charge height L=0.85714D, shell thickness h=0.08929D which corresponds to the combination of 3-3-1-3-2 in Table 4. Table 8 shows the results of the optimized plan of rod-shaped Ta-W EFP at t=240μs.

Table 8. Results of the optimized plan of rod-shaped Ta-W EFP.

| The shape of EFP | v(m/s) | l/d | P   | Q   |
|------------------|--------|-----|-----|-----|
|                  | 2312   | 4.41998 | 0.95929 | 0.21109 |

5. Conclusion

In this paper, the LS-DYNA numerical simulation software is used to study the arc-cone liner different charge structure parameters on the forming of Ta-W EFP. The following conclusions can be drawn:

1) The influence of the structure parameters of the arc-cone liner on the forming of Ta-W EFP is obtained. The velocity v of EFP increases with the increase of R, α, L, h, and decreases with the increase of δ; The length-to-diameter ratio of EFP increases with the increase of L, decreases with the increase of R, α, δ, and first decreases and then increases with the increase of h; The compactness P of EFP first increases and then decreases with the increase of R, α, h, decreases with the increase of δ, and first decreases and then increases with the increase of L; The necking ratio Q decreases with the increase of δ, and first decreases and then increases with the increase of R, α, L, h.

2) The optimal range of each structural parameter is determined. The optimal range of curvature radius R is 1.1D~1.2D; The optimal range of half cone angle α is 65°~71°; The optimal range of thickness δ is 0.02D~0.03D; The optimal range of charge height L is 0.75D~0.9D; The optimal range of shell thickness h is 0.07D~0.14D.

3) The range analysis method is used to get: The primary and secondary order of velocity v is δ, h, L, α, R; The primary and secondary order of length-to-diameter ratio l/d is δ, α, R, L, h; The primary...
and secondary order of compactness $P$ is $h, \delta, L, \alpha, R$; The primary and secondary order of necking ratio $Q$ is $\delta, R, \alpha, L, h$.

(4) According to the results of the orthogonal optimization design, the structural parameters of the optimized plan of rod-shaped Ta-W EFP are determined as follow: curvature radius $R=1.16071D$, half cone angle $\alpha=68.5^\circ$, thickness $\delta=0.02054D$, charge height $L=0.85714D$, shell thickness $h=0.08929D$ whose velocity is $2312m/s$, length-to-diameter ratio is $4.41998$, compactness is $0.95929$ and necking ratio is $0.21109$.

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