Numerical Simulation of Tantalum-Tungsten Alloy for Forming Characteristics of EFP with Liner of Different Tungsten Contents

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Abstract. By LS-DYNA hydrocode, the EFP (Explosively Formed Projectile) forming characteristics of tantalum tungsten alloy are simulated. The EFP forming characteristics of tantalum tungsten alloy with different W contents under typical charge structure are obtained. The curvature range of the liner required for forming solid rod shaped EFP with large aspect ratio is determined, and the influence of tantalum tungsten alloy material’s constitution parameters on EFP forming is analyzed. The forming patterns of tantalum tungsten EFP with different tungsten contents are similar, but the range of outer curvature required for forming a solid EFP is different. The research results can provide references for EFP design and lay foundation for the application of high density tantalum tungsten alloy in the intelligent and smart ammunition.

Keywords: Ordinance science and technology; Explosively Formed Projectile; Tantalum tungsten alloy; Forming characteristic; Numerical simulation.

1. Introduction
Explosively formed projectile (EFP) is an important research area of shaped charge technology. As it is not sensitive to standoff and it can effectively destroy targets within a long distance, it is widely used in terminal sensitive bombs, smart mines and other combat operations. Now EFP plays an more and more important role in modern Ministry warfare[1-3]. The usage of high-density, high-melting point, high-ductility type of liner materials is an important method to improve the penetration performance of EFP. Tantalum and its alloys have a density as high as 16.6g/cm³. With the same kinetic energy, the greater the density, the higher the specific kinetic energy of the projectile. Then the penetration performance will be significantly improved. The relevant researches show that the penetration ability of tantalum liner can be increased by 30–35% compared with copper. Scholars at home and abroad have carried out some researches on the application of tantalum and its alloys in EFP, such as Seong Lee[4], Kim HJ[5], Xuefei Fan[6], Tengfei Guo[7], Zhipeng Zhu[8], etc. The forming characteristics of Tantalum EFP were studied. However, there is little research on the comparison of forming characteristics of different tantalum-tungsten alloy EFPs domestic. The matching relationship between the charge and the liner of different Ta-W alloy is uncertain. It is urgent to study forming pattern and law of EFP with Ta-W alloys of different Tungsten contents and establish the matching relationship between the Ta-W alloy liner and the charge structure, which could provide reference for the design of EFP with high-density alloy liner.

In this paper, nonlinear dynamics hydrocode LS-DYNA is used to carry out the numerical simulation of EFP forming characteristics of tantalum tungsten alloy. The EFP forming characteristics of Ta-W...
alloy with different tungsten contents under typical charge structure are obtained. The curvature range of liner required for forming solid rod EFP is determined. The influence of material parameters of tantalum tungsten alloy on EFP forming is analyzed. The research results can provide reference for EFP design and lay a foundation for the application of high density materials in the field of smart ammunition.

2. Numerical Modeling and Material Parameters

2.1. Geometric Model and Simulation Method

Figure 1. Geometry model of EFP charge structure
Figure 2. Simulation model of EFP charge structure

Figure 1 shows the geometric diagram of the typical EFP charge structure, which composed of casing, charge and liner. The diameter of the charge is noted as $D_c$, the length of the charge is noted as $l$, and the length to diameter ration of the charge is 1.0. The radius of outer and inner curvature are defined as $R_o$ and $R_i$. The liner is made of different tantalum tungsten alloy, with a constant wall thickness of $h$, which equals to the subtraction of $R_o$ and $R_i$. In this paper, the value of the wall thickness of the liner equals to $0.0375D_c$, and thickness of casing equals to $0.08D_c$. Center detonation point is used to ignite the explosive charge. When the control and output conditions are set, it is feasible to simulate the forming of an EFP in LS-DYNA.

2.2. Material Model and Parameters

The simulation model of EFP charge structure is illustrated in Fig.2, which is modeled in the LS-DYNA hydrocode. Figure 2 shows the components of EFP which are modeled with 2D Lagrange algorithm of axisymmetric solid-area weighted shell. On the basis of simulation experience, the mesh size is about 0.5mm per grid. Center detonation point is used in the simulation. The simulation model is consistent with the geometric model.

Table 1. Material models used in numerical simulation

| Component | Material | Density $\rho$ (g/cm$^3$) | Equation of State | Constitutive Model |
|-----------|----------|--------------------------|------------------|-------------------|
| Liner     | Ta-2.5W  | 16.6                     | Gruneisen        | Johnson-Cook      |
|           | Ta-5W    | 16.6                     | Gruneisen        | Johnson-Cook      |
|           | Ta-10W   | 16.6                     | Gruneisen        | Johnson-Cook      |
| Casing    | Steel #45| 7.83                     | Gruneisen        | Johnson-Cook      |
| Charge    | JH-2     | 1.71                     | Jones-Wilkins-Lee| High-Explosive-Burn|

The material and material model of liner, casing and charge are listed in Table 1. JH-2 is a kind of RDX explosive, which adopts the Jones-Wilkins-Lee equation and High-Explosive-Burn constitutive model to describe its detonation behaviour. The behaviour of Tantalum and tantalum tungsten alloys liners are characterized by the Gruneisen Equation of state and Johnson-Cook Constitutive model. The Johnson-Cook model\cite{11, 12} is a widely used constitutive model which incorporates the effect of strain rate dependent work hardening and thermal softening. The Johnson-Cook constitutive relation is given by\cite{9, 10}.
\[ \sigma = \left( \sigma_0 + B \varepsilon'^* \right) \left( 1 + C \ln \frac{\hat{\varepsilon}}{\hat{\varepsilon}_0} \right) \left( 1 - T^* \right) \]  
where \( \varepsilon \) is the plastic strain and the temperature factor \( T^* \) is expressed as

\[ T^* = \frac{T - T_r}{T_m - T_r} \]

Where \( T_r \) is the room temperature, \( T_m \) is melt temperature of the material. \( \sigma_0, B, n, C \) and \( m \) are material-related parameters. And \( \varepsilon \) is effective plastic strain, \( \varepsilon^* = \hat{\varepsilon} / \hat{\varepsilon}_0 \) is the effective plastic strain rate, where \( \hat{\varepsilon}_0 \) is the reference strain rate, the failure model is also included in the Johnson-Cook constitutive model.

| Material    | \( \sigma_0 \) (MPa) | \( B \) (MPa) | \( n \) | \( C \) | \( m \) | \( T_m \) (K) | \( T_r \) (K) | \( \dot{\varepsilon}_0 \) (s\(^{-1}\)) | Reference |
|-------------|----------------------|---------------|--------|-------|-------|-------------|-------------|-----------------|----------|
| Ta          | 220                  | 520           | 0.325  | 0.055 | 0.475 | 3250        | 298         | 1.0             | [11]     |
| Ta-2.5W     | 245                  | 493           | 0.58   | 0.065 | 1.04  | 3250        | 294         | 1.0             | [12]     |
| Ta-5W       | 400                  | 875           | 0.525  | 0.0363| 0.55  | 3250        | 298         | 1.0             | [13]     |
| Ta-10W      | 470                  | 1000          | 0.425  | 0.03  | 0.6   | 3250        | 298         | 1.0             | [13]     |

The parameters of constitutive model for tantalum and tantalum tungsten alloys are listed in Table 2. By comparison, it can be concluded: (1) At the same reference strain rate \( \dot{\varepsilon}_0 \), the yield stress \( \sigma_0 \) of tantalum tungsten alloy increases with the increase of tungsten content; (2) The strain hardening coefficient \( B \) and strain hardening index \( n \) of tantalum tungsten alloy are both greater than pure Tantalum, indicating that with the addition of tungsten, the work hardening effect of Tantalum material is significantly enhanced, and with the increase of W content, the strain hardening coefficient \( B \) shows an growth trend.

### 3. Influence of Liner Material on EFP’s Forming Characteristic

#### 3.1. Ta EFP

Table 3 shows the Forming characteristics of Ta EFP with different relative outer radius curvatures. \( L \), \( D \) and \( v \) are the length, diameter and velocity of the formed EFP. The presented EFP shape are captured at around 200\( \mu \)s. By comparison, it can be seen: (1) When the outer curvature \( R_o/D_c \) of pure Tantalum increases from 0.95 to 1.2, the EFP length decreases gradually, and the length to diameter ratio decreases correspondingly; (2) When the value of \( R_o/D_c \) is less than 1.0, Tantalum EFP will have a fracture tendency in the axial direction due to excessive aspect ratio; (3) When the value of \( R_o/D_c \) is larger than 1.13, the EFP aspect ratio decreases significantly, and the interior part gradually becomes hollow; (4) For pure Tantalum, when \( R_o/D_c \) ranges from 1.08 to 1.13, The formed EFP has a high degree of solidity, and the length to diameter ratio is about 3.0.

| \( R_o/D_c \) | EFP shape | \( v \) (mm/s) | \( L \) (mm) | \( D \) (mm) | \( L/D \) |
|--------------|-----------|---------------|-------------|-------------|---------|
| 0.95         | 1596      | 68.26         | 8.89        | 7.68        |
| 1.00         | 1643      | 42.49         | 9.29        | 4.57        |
Table 4. Forming characteristics of Ta-2.5W EFP with different relative outer radius curvatures

| $R_o/D_c$ | EFP shape | $v$ (mm) | $L$ (mm) | $D$ (mm) | $L/D$ |
|----------|-----------|----------|----------|----------|-------|
| 0.75     |           | 1510     | 75.48    | 8.46     | 8.92  |
| 0.83     |           | 1560     | 36.09    | 9.41     | 3.84  |
| 0.88     |           | 1592     | 27.45    | 10.07    | 2.73  |
| 0.95     |           | 1628     | 20.58    | 11.22    | 1.83  |
| 1.00     |           | 1650     | 19.93    | 12.24    | 1.63  |
| 1.08     |           | 1673     | 19.51    | 13.15    | 1.48  |
| 1.25     |           | 1711     | 18.59    | 15.43    | 1.20  |

Table 4 shows the Forming characteristics of Ta-2.5 EFP with different relative outer radius curvatures. By comparison, it can be seen: (1) When the outer curvature $R_o/D_c$ of Ta-2.5W increases from 0.75 to 1.25, the EFP length decreases gradually, and the length to diameter ratio decreases.
correspondingly; (2) When the value of $R_o/D_c$ is less than 0.83, Ta-2.5W EFP will have a fracture tendency in the axial direction due to excessive aspect ratio; (3) When the value of $R_o/D_c$ is larger than 1.08, the EFP aspect ratio decreases significantly, and the interior part gradually becomes hollow; (4) For Ta-2.5W, when $R_o/D_c$ ranges from 0.88 to 1.00, The formed EFP has a high degree of solidity, and the length to diameter ratio is about 2.7.

3.3. Ta-5W EFP

Table 5. Forming characteristics of Ta-5W EFP with different relative outer radius curvatures

| $R_o/D_c$ | EFP shape | $v$ (mm) | $L$ (mm) | $D$ (mm) | $L/D$ |
|---|---|---|---|---|---|
| 0.83 | | 1525 | 60.76 | 8.92 | 6.81 |
| 0.88 | | 1596 | 36.70 | 9.61 | 3.82 |
| 0.95 | | 1619 | 21.86 | 10.07 | 2.17 |
| 1.00 | | 1653 | 21.08 | 11.46 | 1.84 |
| 1.08 | | 1672 | 20.04 | 12.92 | 1.55 |
| 1.13 | | 1685 | 15.34 | 20.9 | 0.73 |

Table 5 shows the Forming characteristics of Ta-5W EFP with different relative outer radius curvatures. By comparison, it can be seen: (1) When the outer curvature $R_o/D_c$ of Ta-5W increases from 0.83 to 1.08, the EFP length decreases gradually, and the length to diameter ratio decreases correspondingly; (2) When the value of $R_o/D_c$ is less than 0.88, Ta-5W EFP will have a fracture tendency in the axial direction due to excessive aspect ratio; (3) When the value of $R_o/D_c$ is larger than 1.00, the EFP aspect ratio decreases significantly, and the interior part gradually becomes hollow; (4) For Ta-5W, when $R_o/D_c$ ranges from 0.95 to 1.00, The formed EFP has a high degree of solidity, and the length to diameter ratio is about 2.2.

3.4. Ta-10W EFP

Table 6 shows the Forming characteristics of Ta-10W EFP with different relative outer radius curvatures. By comparison, it can be seen: (1) When the outer curvature $R_o/D_c$ of Ta-10W increases from 0.83 to 1.25, the EFP length decreases gradually, and the length to diameter ratio decreases correspondingly; (2) When the value of $R_o/D_c$ is less than 0.88, Ta-10W EFP will have a fracture
tendency in the axial direction due to excessive aspect ratio; (3) When the value of $R_o/D_e$ is larger than 1.00, the EFP aspect ratio decreases significantly, and the interior part gradually becomes hollow; (4) For Ta-10W, when $R_o/D_e$ ranges from 0.88 to 1.00, The formed EFP has a high degree of solidity, and the length to diameter ratio is about 2.8.

**Table 6.** Forming characteristics of Ta-10W EFP with different relative outer radius curvatures

| $R_o/D_e$ | EFP shape | $v$ (mm) | $L$ (mm) | $D$ (mm) | $L/D$ |
|-----------|------------|----------|----------|----------|-------|
| 0.83      |            | 1580     | 48.56    | 9.21     | 5.27  |
| 0.88      |            | 1587     | 24.00    | 8.64     | 2.78  |
| 0.95      |            | 1631     | 20.40    | 11.07    | 1.84  |
| 1.00      |            | 1642     | 19.81    | 12.78    | 1.55  |
| 1.13      |            | 1681     | 18.23    | 15.56    | 1.17  |
| 1.25      |            | 1706     | 17.54    | 17.02    | 1.03  |

### 3.5. Comparison and Discussion

By comparison the forming characteristics of EFP with tantalum and tantalum tungsten alloy liner, it can be inferred:

(1) Under typical charge structure, the tantalum material and constitutive parameters have a great influence on EFP forming characteristics. The forming laws of tantalum tungsten alloys with different Tungsten content are similar, but the outer curvature range required for solid EFPs is different.

(2) For Ta-10W, when $R_o/D_e$ ranges from 0.88 to 1.00, The formed EFP has a high degree of solidity, and the length to diameter ratio is about 2.8. More precise value range of outer curvature should be
determined in the numerical simulation.

4. Conclusion
In this paper, the constitutive model of tantalum and tantalum tungsten alloy was investigated, and the forming characteristics of tantalum tungsten alloy EFP under typical charge structure were numerically simulated by LS-DYNA nonlinear dynamics software. It can be concluded:

(1) At the same reference strain rate $\dot{\varepsilon}$, the yield stress $\sigma_0$ of tantalum tungsten alloy increases with the increase of tungsten content, and the strain hardening coefficient $B$ also has a growth trend with the increase of tungsten content.

(2) With typical EFP charge structure, Tantalum material and material constitutive parameters of the liner have great influence on the EFP forming performance. The forming patterns of tantalum tungsten EFP with different tungsten contents are similar, but the range of outer curvature required for forming a solid EFP is different.

(3) When the range of the outer curvature $R_o/D_c$ is set to $[0.88, 1.13]$, the formed EFP has a rather satisfactory shape with length to diameter ratio of $[2.2, 2.7]$. The outer curvature ranges of the liner corresponding to different tungsten contents to form solid EFPs are obtained by numerical simulation.

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