Multiscale Numerical Simulation of the Shaped Charge Jet Generated from Tungsten-Copper Powder Liner

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Abstract. Formation process of the shaped charge jet of W-Cu powder liner was simulated with smoothed particle hydrodynamics (SPH) method of LS-DYNA software. With the digital image process technique and macro-micro coupling method, a multiscale finite element model was established, and the high speed deformation process of the microstructure driven by explosive detonation in the liner of shaped charge was successfully simulated. The Cu phases were susceptible to serious deformation while the tungsten phase has less deformation. Besides, the temperature field of the microstructure during the shaped charge deforming was calculated, and a discussion of the deformation mechanism of the liner was given. The methods proposed in this paper would be of help in microstructure design of shaped charge materials.

1. Introduction

The linear shaped charge is a kind of shaped charge warhead[1]. After the initiation of detonation, the shaped charge liner collapse, then a high speed jet is formed and stretched in a short time[2]. The Shaped charge jets with high energy and good direction has a strong cutting penetration effect and it is widely applied to the defense industry and civil engineering.[3-6] The shaped charge liner is the carrier of energy, and the property of liner materials acts an important role on the energy accumulation of shaped charge. Therefore, studies on shaped charge material receive great attention in recent years[7-13]. Fe, Cu, Ta, U, W-Cu alloy are all good candidate materials. Especially, the W-Cu material has a high density characteristics and a good ductility capacity[14-15]. Compared with the traditional Cu materials, the tungsten Cu shaped charge liner has more advantages in higher initial density, very short stand off and deep penetration, so it has been extensively investigated. Jamet[15] put forwarded that W alloy with high density and high dynamic ductility can replace the Cu to become a good liner material. Seong[13] studied the penetration performance of forging tungsten Cu shaped charge liner. Jaekowski[16], Lichtenberger[17],et al discussed the influence of processing technology, grain size and purity on W - Cu material jet properties; Zhang[18] found that the density uniformity of the shaped charge liner and tungsten particle size were important factors in affecting penetration depth. Most of these studies based on the experiment result. However, because of the large-deformation dynamics and the complex multi-materials interaction over very a short time[19], some experimental phenomena and results are hard to be observed. Therefore, numerical simulation has become necessary to study the behaviors of the shaped charge jets. Maysele[20] studied the effect of liner porosity on jet properties by using a 2-D hydrodynamics code. Li[21] took advantage of Lagrange function and adaptive mesh method to model the process of jet formation. Huerta et al[22] used an analytical code to investigate the penetration properties of the conical shaped charge and compared it with experimental results. Lei[23]simulated the formation process of the shaped charge jet of tungsten-Cu powder liner by multi-material ALE algorithm. Qiang [24]developed a multi-phase SPH
(MSPH) method to improve the numerical simulation of shaped charge jet. Though some positive achievements have been made on understanding the action of shaped charge jet formation, almost all the previous numerical simulations were for the macro jet formation process, and the microstructure evolution were not taken into account.

In the current study, formation process of the shaped charge jet of W-Cu liner was simulated by SPH method in LS-dyna, firstly. Subsequently, by extracting the load information of the local large deformation region and acting it on a microstructure finite element model, the microstructure evolution at the early formation stage of the jet was successfully captured.

2. Numerical Simulation Model

2.1. Characteristics of the Linear Shaped Charge SPH Model

The geometrical model for a linear shaped charge consists of the liner and explosive, as illustrated in Fig. 1. Because of the symmetrical structure of the linear shaped charge, the model is established using 2D plane strain approximation, which is composed of 8367 SPH elements. As shown in figure 1, the wall thickness is 3 mm; the angle of the liner is 80°; the length of the liner is 30 mm; and the charging height is 32 mm. The material used for the explosive is 8701 explosive. The material model “High Explosive Burn” with an equation of state “JWL” is used for the explosive. The material parameters for the explosive are listed in table 1[25]. The material model for the W-Cu alloy is *MAT_STEINBERG with an equation of state *EOS_GRUNEISEN in LS-DYNA. The material parameters for the liner are listed in table 2[22].
Table 1  The JWL state equation parameters of explosive products.

| ρ/(g·cm⁻³) | D/(km·s⁻¹) | Pₑ/GPa | e/(kg·cm⁻³) | A/GPa | B/GPa | R₁ | R₂ | ω | V₀ |
|------------|-------------|--------|-------------|--------|-------|-----|-----|----|----|
| 1.7        | 8.1         | 29.5   | 8.35        | 581.2  | 6.8   | 4.10| 1.10| 0.34| 1.0|

Table 2  The constitutive model parameters of W-Cu material.

| ρ/(g·cm⁻³) | G₀/GPa | b/s²·kg⁻²³ | b/s²·kg⁻²³ | h | f | a | Tₘ₀/K | γ₀ | σ₀/GPa |
|------------|--------|------------|------------|----|---|---|-------|----|--------|
| 18.98      | 84.4   | 4.739      | 4.739      | 8.056 | 0.001 | 1.5 | 1710  | 2.42 | 0.12   |

2.2. Finite Element Model of the W-Cu Alloys Microstructure

In order to study the response of the microstructure of W-Cu shaped charge liner on experiencing detonation loading, a finite element model based on the actual microstructure of W-Cu alloys needs to be established. By using the Microstructure Oriented Finite Element Software (MOF) designed in our group [26], a finite element model consistent with the real microstructure of W-Cu alloys is generated, as shown in figure 2. This finite element model is composed of 34080 shell finite elements, and the dimensions are 258μm×193μm.

![microstructure of W-Cu alloy](image)

**Figure 2** The establishment of the microstructure finite element model

In this model, the *MAT_STEINBERG* is chosen to model the W and Cu materials. The parameters are given in table 3 and table 4, respectively.

Table 3  The constitutive model parameters of W material.

| ρ/(g·cm⁻³) | G₀/GPa | b/s²·kg⁻²³ | h | f | a | Tₘ₀/K | γ₀ | σ₀/GPa |
|------------|--------|------------|----|---|---|-------|----|--------|
| 19.22      | 160    | 4.70       | 8.06 | 0.001 | 1.838 | 3560  | 2.02 | 0.12   |

Table 4  The constitutive model parameters of Cu material.

| ρ/(g·cm⁻³) | G₀/GPa | b/s²·kg⁻²³ | h | f | a | Tₘ₀/K | γ₀ | σ₀/GPa |
|------------|--------|------------|----|---|---|-------|----|--------|
| 8.93       | 47.7   | 2.83       | 3.77 | 0.001 | 0.635 | 1790  | 2.02 | 0.12   |

2.3. Coupling of the macro and micro numerical models

Based on the simulation of the jet formation, the severe deformation process of the liner is observable, and the load conditions of each region can be obtained accordingly. Extract the load conditions of the region which we concern, e.g. the small red square position in figure 1, and load it into the finite element model of the microstructure, the response of the microstructure of this region under the corresponding loads can be tracked. The coupling method of micro-macro numerical simulation is illustrated in figure 3.
2.4. Heating Mechanism of the Liner
When the explosive charge is initiated, the detonation wave spreads, and the liner material is accelerated and collapsed under the high pressure. At the same time, the temperature of the liner is increased significantly under the action of the shock waves and the severe plastic deformation.

The temperature increase $T_s$ caused by shock waves is calculated as:

$$
T_s = \exp \left[ \left( \frac{\gamma_0}{\gamma V_0} \right) (V_0 - V) \right] \times \left( \frac{1}{2C_v} \int^r_0 \frac{dp(V)}{dv} \right) \times \exp \left[ \left( \frac{\gamma_0}{\gamma V_0} \right) (V - V_0) \right] dV + T_0
$$

where $V_0$ and $V_0$ are volumes of porous materials and dense materials. $p$ and $\gamma_0$ are the pressure in the liner and Gruneisen coefficient of the material, respectively. $C_v$ is the heat capacity at constant volume and $T_0$ is the room temperature.

When pressure unloading, the residual temperature can be obtained from the isentropic adiabatic equation:

$$
T_r = T_s \exp \left[ \left( \frac{\gamma_0}{\gamma V_0} \right) (V_s - V_r) \right]
$$

$T_r$ is the residual temperature after the shock waves. $V_s$ and $V_r$ are liner volumes under the situation of shocks and after shocks.

The increasing temperature of liner $\Delta T$ caused by shock wave is obtained: $\Delta T = T_r - T_0$

The temperature rise $\Delta T_1$ due to plastic deformation can be calculated as:

$$
\Delta T_1 = \frac{\sigma \varepsilon}{\rho C_p} \int^\varepsilon_0 \sigma d\varepsilon
$$

Where $\rho$ and $C_p$ are the density and heat capacity at constant pressure of the material; $\sigma$ and $\varepsilon$ are stress and strain of the liner; $\eta$ is the thermal transformation efficiency.

The general temperature rising is: $\Delta T = \Delta T_1 + \Delta T_2$.

3. Numerical Simulation of Shaped Charge Jet Formation
Upon initiation of the explosive, the detonation wave spreads, and the liner material is accelerated and collapsed under the high pressure. The simulation results shown below demonstrate the progress of jet forming process.

Figure 1(a) shows the initial state of the liner. The explosive is initiated, but the shock wave has no interact with the liner. The liner deformation state at $t = 10\mu$s is presented in figure 4(b). The collapse of the liner material on the centerline generates a jet where the jet tip can travel in excess of 1800m/s. As seen in figure 4(c), the Jet and slug are generated at $t=20\mu$s, and the further jet evolution is illustrated in figure 4(d).
With the continuous flow of the jet, the jet tip accelerates up to 1870m/s. Because of the different speeds of the slug and jet tip, the jet is stretched. It can also be found that the mass of the jets primarily comes from the bottom of the liner, and the part at the top of liner becomes the slug.

![Figure 4. Shaped charge jet forming and stretching](image)

**Figure 4.** Shaped charge jet forming and stretching

### 4. Numerical Simulation for Microstructure Evolution of W-Cu Alloys

#### 4.1. Numerical simulation of the deformation of W-Cu alloys

By using the method described in section 2.3, the deformation behavior of the W-Cu microstructure can be tracked.

The microstructure deformation at \( t=6.8 \mu s \) is presented in figure 5. A serious deformation is found in the finite element model of the W-Cu microstructure under the detonation load. It is clear that there are slip bands on Cu phase, along the boundaries of W phase and W/Cu interfaces. It might be noted that the bands appear on Cu phase but not reach the fracture limit, which is believed to be responsible for its excellent plasticity. On the other hand, there is little plastic deformation in W phase due to its poor ductility. A comparison between the experimental result and the numerical result is shown in Fig. 5, it can be seen that the simulation result agrees well with the corresponding experimental result.

The distribution of the effective stress and effective plastic strain of the microstructure finite element model at \( t=6.8 \mu s \) are shown in figure 6. According to the contour shown in figure 6 (a), the stress value at the W phase is about 1GPa, which is much higher than that of 0.2–0.3GPa in Cu phases. The maximum stress appears at the Cu/W interfaces, up to 1.19GPa. During deformation, the stress in Cu phase is higher than its yield strength 57MPa, while the stress in W phase is far below than its yield strength 1200MPa, which means that plastic deformation occurs in Cu phase primarily. As shown in figure 6 (b), the strain value in the Cu phase is much higher than that of W phase, and the maximum strain value reaches 10.
Figure 5 Comparison of experimental and simulation results

Figure 6 Contours of the v-m stress and effective plastic strain of the model
4.2. Heating effect of W-Cu alloys
The temperature contours due to the heating effect of shock wave and plastic deformation work is shown in figure 7. As shown in figure 7, the temperature at the W skeleton is about 500–600 ℃ while the Cu phase temperature can reach 400 ~ 550 ℃. The W generates more energy when plastic deformation occurs for its high strength. Besides, the heat capacity and thermal conductivity of W are 136 J/(kg • K) and 174 W/(m • K) while that of the Cu are 385 J/(kg • K) and 403 W/(m • K) respectively. Because of the high plastic deformation energy with the low heat capacity and thermal conductivity, the temperature of W phase is higher than that of Cu. But the temperature of W is much lower than its melting point of 3387 ℃ while the Cu phase has reached 0.4 times of the melting point, 1083 ℃, i.e. the dynamic recrystallizational temperature. Under the high-speed service conditions, the refined recrystallizational Cu grains make great contribution to the superplasticity conditions during jet formation.

![Figure 7 Contours of the temperature of the W-Cu microstructure model](image)

5. Conclusions
1. In this paper, a 2D shaped charge jet model is established using SPH elements. The formation process of the shaped charge jets is simulated, which is in good agreement with the experimental results.

2. Multiscale numerical simulation by Macro-micro coupling is accomplished by extracting the load of a micro region onto the microstructure model. Deformation of the microstructure of the W-Cu
liner is successfully captured. It is found that the slip band appears on the Cu phase while the W phase changes little.

3. The heating effect of the W-Cu microstructure, due to shock wave and plastic deformation work, is studied, indicating that the temperature of Cu is higher than 0.4 times of its melting point, thus meeting the recrystalline conditions and making great contribution to its superplasticity conditions during the jet formation.

6. Acknowledgements
The authors would like to acknowledge Professor Li shukui and Dr. Liu jinxu for helping in this research. This research is also supported by Dr. Guo wenqi for providing W-Cu microstructure pictures.

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