Investigation of Explosion Simulation on Jet Forming of ZrCuNiAlAg Amorphous Alloy Liner with Eccentric Sub-hemisphere Structure

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Abstract. Structure and material are the two key factors affecting the jet forming of the liner. To investigate the influence of new structure and new materials on the jet forming of the liner, a shaped charge model with eccentric sub-hemisphere structure based on ZrCuNiAlAg amorphous energetic alloy was proposed. The jet forming law of eccentric sub-hemispherical liner is studied by fixing other parameters and changing the structure parameters of liner in turn by means of AUTODYN numerical simulation software. The simulation results show that the eccentric sub-hemispherical liner of ZrCuNiAlAg amorphous alloy can form a shaped jet very well by using gathering energy effect. The speed of the shaped jet decreases gradually with time, and the shape of the jet changes from short and thick to long and thin. The curvature radius, eccentricity and wall thickness have a significant effect on the jet forming performance of ZrCuNiAlAg amorphous alloy. As the curvature radius or wall thickness increase, the tip velocity and the length diameter ratio (LDR) of the jet will decrease gradually, while with the increase of the eccentricity of the liner, the jet tip velocity and the LDR will increase gradually. The analysis of simulation data shows that the change of eccentricity has the greatest influence on the jet LDR. When the eccentricity increases from 25 mm to 39 mm, the jet LDR increases by 74% at 60\,\mu s. The wall thickness has the greatest influence on the tip velocity of the jet. When the wall thickness increases from 1.4 mm to 3.8 mm, the tip velocity of the jet at 60\,\mu s decreases by 29.77%. The results of this paper can be used for scientific reference in the structural design of this kind of liner.

1. Introduction

The liner is the core component of shaped charge. The structure and material are the two key factors affecting the performance of the liner. For more than 100 years, scholars have been carrying out exploration and research on the selection of the liner materials. The liner materials have experienced the changes of high density single metal materials, non-metal materials with low density, composite materials and energetic materials. Especially in the past 20 years, the application of energetic reactive materials in liner has become a research hotspot in the field of shaped charge. Some scholars have carried out theoretical analysis and experimental research on the formulation, manufacturing process, mechanical properties, energy release and composite damage mechanism of metal/fluoropolymer energetic materials\textsuperscript{1,5} (such as PTFE/Al) and metal-based energetic materials\textsuperscript{6-8} (such as Al/Ni). Since Duwez\textsuperscript{9} first prepared the world Au-Si amorphous alloy by means of rapid cooling of molten metal in 1960, the amorphous alloy has shown a broad application prospect for more than half a
century because of its unique atomic structure and excellent performance. Zirconium based (Zr-based) amorphous alloy is a newly developed energetic material, which has better mechanical properties and good energy release properties than metal/fluoropolymer and metal-based active energetic materials. It has great application potential in energetic fragments\cite{10-11}, armour piercing core\cite{12-15}, and especially in the design of new shaped charge jet materials\cite{16-20}.

The shape of the liner is also a long-term concerned focus of the scholars in the field of shaped charge. Different liner shapes have a crucial influence on jet morphology, velocity gradient and maximum stretch length\cite{21}. At present, the conical liner is widely used in shaped charge warhead. Relevant research shows that the eccentric sub-hemispherical liner has a unique advantage in the forming of shaped jet due to its large curvature radius and long generatrix. Curvature radius, eccentricity and wall thickness are the three most important factors that restrict the jet forming performance of eccentric sub-hemispherical liners. Yao\cite{22-23} and Yi\cite{24} respectively studied the jet forming performance of eccentric sub-hemispherical copper and molybdenum liner, which has a good guiding significance for the structural design of such liners.

In this paper, a new Zr-based amorphous alloy energetic material and a good liner geometry are combined by means of numerical simulation. That is, the explosive forming process of the eccentric sub-hemispherical liner of Zr-based amorphous alloy is studied, and the influence of various factors on the jet forming is explored, which could provide a scientific reference for the liner structure design of this material.

2. Model of Simulation

2.1. Structure Model of Shaped Charge (SC)

The structure of Zr-based amorphous alloy eccentric sub-hemispherical SC is shown in Figure 1, which is mainly composed of explosive charge and the liner. The charge diameter (D) is 80mm, and the height of the charge (H) is 96mm. The geometrical parameters of the liner with an eccentric sub-hemispherical structure and constant wall thickness include the radius of arc curvature (r), the eccentricity (e) and the wall thickness (δ). The SC is detonated by central point initiation mode. Different simulation schemes are designed by changing the curvature radius, eccentricity and wall thickness of the liner structure, and the influence of them on the jet forming is studied.

2.2. Finite Element (FE) Calculation Model

The FE calculation model of eccentric sub-hemispherical SC established by AUTODYN software is shown in Figure 2. It is assumed that the explosive, liner and air are homogeneous continuous media, and the whole explosion process is adiabatic. The effect of gravity on the jet is ignored. Considering the axisymmetry of the entire FE model and the explosion load, in order to save the calculation time, a two-dimensional axisymmetric model is used in the simulation for computational efficiency. A total of 63650 elements were created within the numerical analysis of the ANSYS which provided a sufficient mesh density for the calculation. Because of the high strain rate and high overload process in the
formation of damage element of SC, Arbitrary Lagrange Euler (ALE) algorithm is used in numerical simulation to calculate the formation process of shaped jet involving large grid deformation and material flow. Euler algorithm is used for the explosive, the liner and the air. Mm-mg-ms unit system is used in the modeling process.

2.3. Material Model and Equation of State (EOS)
8701 explosive is used as the main charge, with a density of 1.69g/cm³ and a detonation speed of 8425m/s. The constitutive relation is described in the form of High-Explosive-Burn. The EOS of the explosive is chosen as JWL and the material parameters are shown in Table 1. The liner material is ZrCuNiAlAg amorphous alloy, the EOS of which is polynomial in JH-2 model. The material parameters of the liner are shown in Table 2. The Euler domain is filled by air, and the EOS of which is Ideal Gas. The air material parameters are shown in Table 3. The boundary condition of the air (Euler) domain is set as “Flow_out (ALL EQUAL)” to eliminate the boundary effect.

Table 1. Parameters of the 8701 explosive.

| Material         | ρ (g/cm³) | D (m/s³) | PcJ/(GPa) | E/(GPa) | A/(GPa) | B/(GPa) | R1 | R2 | ω | V₀ |
|------------------|----------|----------|-----------|---------|---------|---------|-----|-----|----|----|
| 8701 explosive    | 1.69     | 8425     | 29.6      | 8.499   | 524.23  | 7.678   | 4.2 | 1.1 | 0.34 | 1.00 |

Table 2. JH-2 material parameters of ZrCuNiAlAg amorphous alloy.

| Parameter | P (g/cm³) | A₁ (kJ/kg) | A₃ (kJ/kg) | G (kPa) | B | M | D₁ | nₑ (kPa) | A₂ (kJ/kg) | Tₑ (kPa) | A | C | N | D₂ |
|-----------|-----------|------------|------------|---------|----|---|-----|----------|------------|-----------|----|---|---|----|
| Value     | 6.581     | 1.117×10⁸  | 8.044×10⁹  | 3.704×10⁹ | 0.258 | 0.59 | 0.005 | 3.467×10⁹ | 4.037×10⁸  | 1.117×10⁸  | 0.0044 | 2.432 | 1 |

Table 3. Material parameters of air.

| Material | P (g/cm³) | γ | Cₚ (kJ/kg·K) | Cᵥ (kJ/kg·K) | T (K) | E₀ (kJ/kg⁻¹) |
|----------|-----------|---|--------------|--------------|------|--------------|
| Air      | 1.225     | 1.4 | 1.005 | 0.718 | 288.2 | 2.068×10⁵   |

3. Analysis of Influencing Factors of Jet Forming

3.1. Radius of Curvature

Figure 3. The jet forming process with different curvature radius.

Figure 4. The jet morphology of different curvature radius.

The wall thickness and eccentricity of the liner are fixed to 2.6mm and 37mm, respectively. The jet forming process of ZrCuNiAlAg amorphous alloy liner is simulated when the curvature radius of the liner is 90mm, 95mm, 100mm, 105mm and 110mm, respectively. The jet forming process...
corresponding to the aforementioned curvature radius are shown in Figure 3. The shaped jets of ZrCuNiAlAg amorphous alloy liners with different curvature radius at 60 µs are shown in Figure 4. It can be seen from Figure 4 that the eccentric sub-hemispherical liner of ZrCuNiAlAg amorphous alloy can form a shaped jet with good morphology at 60µs. And the jet length decreases as the curvature radius increases. The jet length when the curvature radius is 110 mm is about 66.1% of that when the curvature radius is 90 mm. The tip velocity and the length diameter ratio (LDR) of the jet under different curvature radius with time are shown in Figure 5 and Figure 6.

**Figure 5.** The jet tip velocity with time under different curvature radius.

**Figure 6.** The jet LDR with time under different curvature radius.

Figure 5 and Figure 6 show that during the process from collapse to the formation of the jet, the tip velocity decreases while the LDR increases gradually with time. Taking the curvature radius of 100 mm as an example, the tip velocity of the shaped jet is 4330 m/s at 60 µs, which is about 7.5% lower than that of 4680 m/s at 30 s, while the LDR increases from 1.5 to 8.1, which is about 4.4 times higher. Both the tip velocity and the LDR of the shaped jet are affected by the curvature radius of the liner. With the increase of the curvature radius, both the two parameters of the shaped jet decrease gradually. This trend can also be seen from the shaped jet parameters of the eccentric sub-hemispherical liner (see Table 4) under different curvature radius at 60 µs. The jet tip velocity decreases by 6.48% and the LDR decreases by 18.21% at 60 µs when the curvature radius increases from 90 mm to 110 mm.

| Curvature radius / (mm) | 90    | 95    | 100   | 105   | 110   |
|------------------------|-------|-------|-------|-------|-------|
| Tip velocity / (m/s)   | 4415  | 4327  | 4330  | 4255  | 4129  |
| LDR                    | 9.17  | 9.0   | 8.1   | 7.8   | 7.5   |

**3.2. Eccentricity**

The wall thickness and curvature radius of the liner are fixed to 2.6 mm and 100 mm, respectively. The jet forming process of ZrCuNiAlAg amorphous alloy liner is simulated when the eccentricity of the liner is 25 mm, 30 mm, 35 mm, 37 mm, and 39 mm, respectively. The jet forming process corresponding to the aforementioned eccentricity are shown in Figure 7. The shaped jets of ZrCuNiAlAg amorphous alloy liners with different eccentricity at 60 µs are shown in Figure 8.
As we can see from Figure 8, the jet length increases gradually with the increase of the eccentricity. By 60 μs, the jet length when the eccentricity is 39 mm is about 1.65 times of that when the eccentricity is 25 mm. The tip velocity and the LDR of the jet under different eccentricity with time are shown in Figure 9 and Figure 10.

Table 5. The shaped jet parameters under different eccentricity (60μs).

| Eccentricity / (mm) | 25   | 30   | 35   | 37   | 39   |
|--------------------|------|------|------|------|------|
| Tip velocity / (m/s) | 4179 | 4207 | 4275 | 4330 | 4355 |
| LDR                | 5    | 5.9  | 7.2  | 8.1  | 8.7  |
3.3. Wall Thickness

The curvature radius and eccentricity of the liner are fixed to 100 mm and 37mm, respectively. The jet forming process of ZrCuNiAlAg amorphous alloy liner is simulated when the wall thickness of the liner is 1.4mm, 2.0mm, 2.6mm, 3.2mm and 3.8mm, respectively. The jet forming process corresponding to the aforementioned wall thickness are shown in Figure 11. The shaped jets of ZrCuNiAlAg amorphous alloy liners with different wall thickness at 60 μs are shown in Figure 12.

![Figure 11](image1.png)

**Figure 11.** The jet forming process with different wall thickness.

![Figure 12](image2.png)

**Figure 12.** The jet morphology of different wall thickness.

It can be seen from Figure. 12 that the length and diameter of the jet become shorter and larger gradually with the increase of the wall thickness. By 60 μs, the jet length when the wall thickness is 3.8 mm is about 78.07% of that when the wall thickness is 1.4 mm. The tip velocity and the LDR of the jet under different wall thickness with time are shown in Figure 13 and Figure 14.

![Figure 13](image3.png)

**Figure 13.** The jet tip velocity with time under different wall thickness.

![Figure 14](image4.png)

**Figure 14.** The jet LDR with time under different wall thickness.

Figure. 13 and Figure. 14 illustrate that during the process from collapse to the formation of the jet, the tip velocity decreases while the LDR increases gradually with time. Taking the wall thickness of 2.6 mm as an example, the tip velocity of the shaped jet is 4330 m/s at 60μs, which is about 7.62% lower than that of 4660 m/s at 30 μs, while the LDR increases from 1.5 to 8.1, which is about 4.4 times higher. Both the tip velocity and the LDR of the shaped jet are affected by the wall thickness of the liner. As the wall thickness increases, both the two parameters of the shaped jet decrease gradually. This trend can also be seen from the shaped jet parameters of the eccentric sub-hemispherical liner(see
Table 6) under different wall thickness at 60 µs. The jet tip velocity decreases by 29.77% and the LDR decreases by 34.78% at 60 µs when the wall thickness increases from 1.4 mm to 3.8 mm.

Table 6. The shaped jet parameters under different wall thickness (60 µs).

| Wall thickness / (mm) | 1.4  | 2.0  | 2.6  | 3.2  | 3.8  |
|----------------------|------|------|------|------|------|
| Tip velocity / (m/s) | 5304 | 4704 | 4330 | 3950 | 3725 |
| LDR                  | 9.2  | 8.4  | 8.1  | 6.8  | 6.0  |

4. Conclusion
(1) The eccentric sub-hemispherical liner of ZrCuNiAlAg amorphous alloy can form a shaped jet very well by using the gathering energy effect. As a whole, the tip velocity of the shaped jet decreases gradually with the simulation time, and the jet shape changes from short and thick to long and thin, that is, the jet LDR increases. From 30 µs to 60 µs, the tip velocity of the shaped jet decreases by 7.33% on average, and the LDR increases by 4.2 times on average.
(2) The curvature radius, eccentricity and wall thickness have a significant effect on the jet forming performance of ZrCuNiAlAg amorphous alloy. Simulation results show that the tip velocity and the LDR of the jet will decrease gradually with the increase of curvature radius or wall thickness, while the jet tip velocity and the LDR will increase gradually with the increase of the eccentricity of the liner.
(3) The eccentricity has the greatest influence on the jet LDR. When the eccentricity increases from 25 mm to 39 mm, the jet LDR increases by 74% at 60 µs. The wall thickness has the greatest influence on the tip velocity of the jet. When the wall thickness increases from 1.4 mm to 3.8 mm, the tip velocity of the jet at 60 µs decreases by 29.77%.

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