Numerical Simulation on Jet Forming and Penetration Performance of Several Amorphous Energetic Alloy Liner with Typical Structures

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Abstract. The structure and material of the liner are the key factors that affect the forming and penetration ability of the jet. In order to study the influence of new energetic materials and typical liner shapes on jet forming and penetration behavior, this paper takes ZrCuNiAlAg amorphous alloy as the liner material and establishes four shaped charge (SC) models with conical, sub-hemispherical, eccentric sub-hemispherical and hypercumulative liners respectively. The jet forming law and its penetration process against the concrete target plates under different liner shapes are studied based on the AUTODYN numerical simulation software. The results show that a stable jet can be formed from ZrCuNiAlAg amorphous alloy liner under the Mohaupt effect, but the jets produced by liners with different structures differ quite a lot. Under the same conditions including charge diameter, charge length diameter ratio and wall thickness, the tip velocity, the tip-tail velocity difference and the length of the jet formed by conical and hypercumulative liners are significantly higher than those of sub-hemispherical and eccentric sub-hemispherical liners. The jet length of the hypercumulative liner is the longest while that of the eccentric sub-hemispherical liner is the shortest. The hypercumulative jet can penetrate a concrete target plate with 400mm thickness at 250μs, and the jets formed by conical, sub-hemispherical and eccentric sub-hemispherical liners basically stops the penetration ability at 300μs. In terms of penetration depth, the hypercumulative liner is the largest and the sub-hemispherical liner is the smallest. The sub-hemispherical liner gets the largest perforation aperture. The eccentric sub-hemispherical liner gets the best comprehensive effect of penetration and expansion against the concrete target. The results of this paper can be used for reference in the structural design of the amorphous alloy liner.

1. Introduction

The liner is the core component of shaped charge (SC). The structure and material are the two key factors affecting the jet forming and penetration 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 SC. 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 [1-5] (such as PTFE/Al) and metal-based energetic materials [6-8] (such as Al/Ni). Since Duwez [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 [10-11], armour piercing core [12-15], and especially in the design of new SC jet materials [16-20].

The structural shape of the liner is also a long-term concerned focus of the scholars in the field of SC. Different liner shapes have a crucial influence on jet morphology, velocity gradient and maximum stretch length [21]. Wang [22] et al. conducted numerical simulation and steel target penetration test on the penetration characteristics of the sub-hemispherical liner with different materials. Chen [23] et al. studied the forming and penetration process of the sub-hemispherical liner in Explosively Formed Projectile (EFP) under different charging conditions. Fu [24] et al. studied the main factors affecting the jet forming effect of the sub-hemispherical liner. 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. Yao [25-26] and Yi [27] 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. Based on the traditional SC theory, Minin [28], a Russian scholar, created the field of hypercumulation SC by proposing and defining the hypercumulative jet phenomenon. According to theoretical calculation of Xu [29] et al., the velocity, effective mass and penetration ability of the hypercumulative jet are far greater than those of the conventional jet.

Since the application of new Zr-based amorphous alloy materials in the field of SC, there has been no systematic study on the influence of different liner shapes on the jet forming and penetration ability of this kind of materials. In this paper, the AUTODYN finite element (FE) analysis technology is used to simulate the jet forming and the penetration ability against concrete target plate of Zr-based amorphous alloy liner with several typical structures, such as conical, sub-hemispherical, eccentric sub-hemispherical and hypercumulative liner, so as to provide a scientific reference for the accurate structural design of this kind of energetic liner.

2. Model of simulation

2.1. Structure model of SC

The structure of Zr-based amorphous alloy SC is shown in figure 1. Four kinds of SC structures with conical liner, sub-hemispherical liner, eccentric sub-hemispherical liner and hypercumulative liner respectively are designed. The SC is mainly composed of the explosive charge and the liner, without considering the influence of charge shell on jet forming. The charge diameter is 80mm and the length diameter ratio of the charge is 1.2. The uniform wall thickness design scheme is adopted for the liner, and the thickness is 1.8mm. The SC is detonated by central point initiation mode.

(a) Conical liner (b) Sub-hemispherical liner (c) Eccentric sub-hemispherical liner (d) Hypercumulative liner

Figure 1. Four typical shaped charge structures.

2.2. Calculation model of FE

The FE calculation models of SC with four kinds of different structures are established by AUTODYN software. 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 four FE models and the explosion load, in order to save the calculation time, a two-dimensional axisymmetric model is used in the simulation for computational efficiency. 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.

To investigate the jet penetration performance, this paper takes the concrete target as the penetration simulation object. Lagrange algorithm is used for the concrete target plate, the thickness of which is set to 400mm. The standoff distance are all set to 2 times of the charge diameter. The contact is set as Lagrange/Lagrange. In order to save the calculation time, the “mapping + extraction” method is used to save the shaped jet just running to the target plate (but not yet contacted), and then extract it to complete the simulation of penetration process directly when necessary. figure 2 shows the FE model of shaped jet produced by conical liner penetrating the concrete target plate.

![Figure 2. The FE model of shaped jet produced by conical liner penetrating the concrete plate.](image)

### 2.3. Material model and Equation of State (EOS)

8701 explosive is used as the main charge, with a density of 1.69 g/cm$^3$ and a detonation speed of 8425 m/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$^{[4-5]}$ 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$^{[30]}$ are shown in table 2. The Euler domain is filled by air, and the EOS of which is Ideal Gas. The air material parameters$^{[5]}$ 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. Iron is used as the auxiliary liner material in the hypercumulative shaped charge structure. The Shock EOS and Johnson-Cook strength model are used to describe the iron material. The target material is CONC-35MPA concrete, which is described by the p alpha EOS, RHT strength model and failure model. The target material parameters are shown in table 4.

### Table 1. Parameters of the 8701 explosive.

| Material           | $\rho$ (g/cm$^3$) | $D$ (m/s$^3$) | $PCJ$ (GPa) | $E$ (GPa) | $A$ (GPa) | $B$ (GPa) | $R_1$ | $R_2$ | $\omega$ | $v_0$ |
|--------------------|------------------|---------------|-------------|-----------|-----------|-----------|-------|-------|----------|-------|
| 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$^{[30]}$.

| Parameter | $\rho$ (g/cm$^3$) | $A_1$ (kPa) | $A_2$ (kPa) | $G$ (kPa) | B | M | D | $\sigma_{300}$ (kPa) | $A_5$ (kPa) | $T_1$ (kPa) | A | C | N | Dc |
|-----------|------------------|-------------|-------------|-----------|---|---|---|---------------------|-------------|-------------|---|---|---|----|
| Value     | 6.581            | 1.117×10$^9$| 8.044×10$^9$| 3.594×10$^9$| 0.258 | 0.39 | 0.005 | 3.467×10$^9$ | 4.037×10$^9$ | 1.117×10$^9$ | 1.397 | 0.0044 | 2.432 | 1   |
Table 3. Material parameters of the Air\textsuperscript{[5]}.\n\begin{center}
\begin{tabular}{ccccccc}
\hline
Material & $\rho$/(g/cm$^3$) & $\gamma$ & $C_V$(kJ/kg·K) & $C_p$(kJ/kg·K) & T(K) & $E_0$(kJ/kg$^{-1}$) \\
\hline
Air & 1.225 & 1.4 & 1.005 & 0.718 & 288.2 & $2.068\times10^5$ \\
\hline
\end{tabular}
\end{center}

Table 4. Material parameters of the target plate.
\begin{center}
\begin{tabular}{cccc}
\hline
Name & Material & Density $\rho$/g/cm$^3$ & Bulk Modulus $A_1$/kPa & Shear Modulus $G$/GPa \\
\hline
Target plate & CONC-35MPA & 2.75 & $3.527\times10^7$ & $1.67\times10^7$ \\
\hline
\end{tabular}
\end{center}

3. Analysis of simulation results

3.1. The jet forming process

Although the shapes of the liners are different, they all have experienced the process of collapse deformation, normal closure and axial elongation under the action of explosive detonation products. For comparison, figure 3 shows the jet forming process of the liners with different structures, and three typical simulation moments, namely 0μs, 25μs and 50μs. Remove the explosive detonation products and the air, and extract the shaped jets obtained by simulation before touching the targets, as shown in figure 4.

Figure 3. The jet forming process of different SC structures.
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(a) The conical liner (b) The sub-hemispherical liner (c) The eccentric sub-hemispherical liner (d) The hypercumulative liner
Figure 4. The morphology of shaped jets.

It can be seen from figure 3 and figure 4 that at 50μs after the detonation of SC, stable jets can be formed from the four kinds of liners, but the jets morphology are quite different. Among them, the jet formed by a conical liner is like a spindle with one slender end and one blunt end. The jet formed by a sub-hemispherical liner is hollow and like a test tube. The tip of the jet is smooth and the tail is evaginated. There are two less obvious granular tail wings along the evaginated direction. The jet formed by the eccentric sub-hemispherical liner is the shortest, with a shape like a rocket. The tip of the jet is sharp and the tail has bifurcations where there are two more obvious granular tail wings. The jet morphology formed by the hypercumulative liner is the most complex, which is close to a spindle, but the shape is rough. There are two symmetrical granular tail wings around the middle and rear part of the jet respectively. The former one is thick, the latter one is thin, and there are slight bifurcations in the tip part of the jet.

The parameters of shaped jets formed by four different liners before hitting the target are shown in table 5.

Table 5. The parameters of shaped jets formed by four different liners before hitting the target.

| Shape of the liner       | Tip velocity $V_t$ (m/s) | Tail velocity $V_t$ (m/s) | Tip-tail velocity difference $\Delta V$ (m/s) | Jet length $L$ (mm) | Tip diameter $D_t$ (mm) | Tail diameter $D_t$ (mm) |
|-------------------------|--------------------------|---------------------------|----------------------------------------------|---------------------|------------------------|------------------------|
| Conical                 | 6145                     | 1586                      | 4559                                         | 142                 | 2.5                    | 8.6                    |
| Sub-hemispherical       | 4430                     | 2196                      | 2234                                         | 109                 | 8                      | 16                     |
| Eccentric sub-hemispherical | 4160                   | 2120                      | 2040                                         | 92                  | 4                      | 16                     |
| Hypercumulative         | 5406                     | 1165                      | 4241                                         | 163                 | 4                      | 16                     |

It can be seen from figure 4 and table 5 that the tip velocity of the jet formed by the conical liner is the highest. The tip velocity of the jet formed by the sub-hemispherical liner is close to that of the eccentric sub-hemispherical liner which is lower than the other two kinds of liners. The tip-tail velocity difference of the jet formed by the conical liner and the hypercumulative liner is significantly higher than that of the sub-hemispherical liner and the eccentric sub-hemispherical liner. Therefore, the first two kinds of jets have obvious stretching effect in the process of motion, and their length is significantly larger than the latter two kinds. The jet formed by the hypercumulative liner gets the longest length.

3.2. The jet penetration process
The jet which contact the target plate almost is extracted by “mapping” method in AUTODYN to improve the simulation efficiency. The concrete target plate model with a thickness of 400mm is established, and four kinds of extracted shaped jets are imported to simulate the penetration process against the concrete target plate respectively, as shown in figure 5. Among them, the jet produced by a sub-hemispherical liner diverges during the penetration process into the concrete target and gets the shortest penetration depth. The surface of the penetrated target plate is not smooth and there are some pits caused by the impact of the jet particles due to the granular tail wings in the tail of the jet produced by the eccentric sub-hemispherical liner and the hypercumulative liner. From the perspective of the internal shape of the perforation, the jets produced by the conical and hypercumulative liners are slender and have large tip velocity, so the perforations in the concrete target are all approximately...
cylindrical shape with little change in the aperture. When the jet tip lose the ability to penetrating the target continuously because of the short length, large tail diameter and small tip-tail velocity difference of the jets formed by the sub-hemispherical and eccentric sub-hemispherical liners, the following jet tail with larger diameter and smaller velocity cannot further increase the penetration depth which makes it flow around, causing the perforation diameter of the target plate changes significantly. The jet perforation formed by the eccentric sub-hemispherical liner looks like a “wine bottle” with thin bottom and thick middle, while that of the sub-hemispherical liner looks like a “fist”. Figure 6 shows the penetration depth curve of four kinds of shaped jets with time.

![Penetration process of four kinds of shaped jets to the concrete targets.](image)

Figure 5. The penetration process of four kinds of shaped jets to the concrete targets.

![Penetration depth curve with time.](image)

Figure 6. The penetration depth curve with time.
As shown in figure 6, the jet begins to penetrate the concrete target plate at $0\mu$s. The depth-time curve becomes gentle gradually with the increase of time, and the slope of the curve decreases gradually, indicating that the jet penetration ability decreases with the decrease of velocity. The specific reasons are as follows: The tip velocity of the jet is larger, the penetration ability is stronger, and the penetration depth changes faster in the initial stage than the other stages. The tip velocity of the jet decreases sharply with the penetration process. The kinetic energy of the jet decreases continuously. The jet energy loses and consumes gradually and the penetration process of the target plate slows down gradually. The numerical simulation results show that the penetration of the jets formed by the conical, eccentric sub-hemispherical and sub-hemispherical liners basically stop at $300\mu$s, and the jet velocity drops below 300 m/s. The jet penetration depth of the hypercumulative liner is less than that of the conical liner before $180\mu$s, while after that moment, it exceeds the latter. The jet of the hypercumulative liner successfully penetrates the target plate with a thickness of 400mm at $250\mu$s, and still has a storage velocity of 1000 m/s at that time. Therefore, from the perspective of penetration depth, the damage ability of SC with different structures is in order of the hypercumulative liner, the conical liner, the eccentric sub-hemispherical liner and the sub-hemispherical liner. The jet penetration results to the concrete target plate of four kinds of liners with varying structures are shown in table 6.

Table 6. The jet penetration results to the concrete target plate of four kinds of liners with varying structures.

| SC Structures                  | Penetrate through or not | Penetration depth h/mm | Average perforation diameter d/mm |
|-------------------------------|--------------------------|------------------------|----------------------------------|
| Conical liner                 | No                       | 377                    | 51.7                             |
| Sub-hemispherical liner       | No                       | 207                    | 104.3                            |
| Eccentric sub-hemispherical liner | No                      | 344                    | 96.8                             |
| Hypercumulative liner         | Yes                      | $>400$                 | 39.7                             |

To sum up, the conical and hypercumulative liners could produce jets with higher tip velocity and tip-tail velocity difference before hitting the target. In particular for the hypercumulative liner, the effective mass of the jet is increased due to the auxiliary liner, so the penetration depth is much greater. As far as the penetration aperture is concerned, the penetration aperture of the sub-hemispherical liner is the largest, but with an insufficient penetration depth. While the eccentric sub-hemispherical liner combines the characteristics of the above three structures, which not only has a large penetration depth, but also has a high penetration aperture, and the comprehensive damage effect of penetration and expansion to the concrete target plate is much more obvious.

4. Conclusions
- A stable jet can be formed from Zr-based amorphous alloy liner under the Mohaupt effect, but the jets produced by liners with different structures differ quite a lot. The jets formed by conical and hypercumulative liners are spindle shaped, among which the former are smooth and the latter are rough. Jets formed by sub-hemispherical liners are hollow tube shaped. Jets formed by eccentric sub-hemispherical liners are rocket shaped. Jets formed by eccentric sub-hemispherical liners and hypercumulative liners have obvious granular tail wings.
- Under the same conditions including charge diameter, charge length diameter ratio and wall thickness, the tip velocity, the tip-tail velocity difference and the length of the jet formed by conical and hypercumulative liners are significantly higher than those of sub-hemispherical and eccentric sub-hemispherical liners. The jet length of the hypercumulative liner is the longest while that of the eccentric sub-hemispherical liner is the shortest.
- The jet produced by the hypercumulative liner can successfully penetrate a concrete target plate with a thickness of 400mm at $250\mu$s and still has a storage speed of 1000 m/s. The jets formed by
conical, eccentric sub-hemispherical and sub-hemispherical liners basically stops the penetration behavior at 300\(\mu\)s, and the storage speed of the jet decreases to below 300 m/s. In terms of penetration depth, the hypercumulative liner is the largest and the sub-hemispherical liner is the smallest. The sub-hemispherical liner gets the largest perforation aperture. The eccentric sub-hemispherical liner gets the best comprehensive effect of penetration and expansion against the concrete target.

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