Numerical Simulation of Jet Forming Characteristics of Energetic Liner Based on Smoothed Particle Hydrodynamics Algorithm

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Abstract. To study the jet forming characteristics of energetic material liner, in this paper, using AUTODYN simulation software and smoothed particle hydrodynamics (SPH) algorithm, the jet forming process of traditional metal Al liner and PTFE/Al energetic liner with different shapes, different cone angles and different thickness was simulated. The results show that the morphologies of PTFE/Al energetic jet and Al inert jet are significantly different, PTFE/Al jet has divergence compared with Al jet. With the increase of cone angle of liner, the velocity of jet tail increases, the velocity of jet head and the length of penetrator decrease. As the liner thickness increases, the head and tail velocity of the jet decrease, and the length of the penetrator increases.

1. Introduction
The application of energetic materials, especially polytetrafluoroethylene (PTFE) based materials, in the field of shaped charge provides a new technical way to improve the aftereffect of jet penetration, which has been widely concerned by scholars. Different from the traditional metal jet, the energetic jet can achieve the combined damage of kinetic energy and chemical energy to the target.

Baker et al. [1], Daniels et al. [2], Xiao Jiang Guang [3] who use the PTFE-based energetic liner shaped charge damage concrete target test found that the jet in the penetration of the target at the same time will occur implosion effect, enhance the damage power. Wang et al. [4] simulated the jet forming process of PTFE/Al liner by Euler algorithm, and carried out X-ray photography test, found that compared with the metal jet, the energetic jet had thicker diameter and poorer ductility. Chen et al. [5] carried out the numerical simulation and experimental verification of PTFE/Cu liner jet forming, and proposed the non-condensable characteristics of PTFE-based liner jet forming for the first time.

According to the published literature, the research on PTFE-based energetic liner mainly focuses on the damage effect of jet on different targets. However, there are few studies on the jet forming characteristics of energetic liner, the influence of liner material and structural parameters on jet forming. Therefore, this paper conducts a simulation study on the difference between energetic jet and inert jet forming, and also studies the influence of liner shape, cone angle and thickness on jet forming and performance parameters through numerical simulation. The research results have certain reference value for the design of energetic liner.
2. Numerical Simulation

2.1. Simulation Model

Smoothed particle hydrodynamics (SPH) algorithm can not only accurately describe the material interface, but also effectively avoid the grid distortion and negative volume in the finite element method, which is suitable for describing the problem of large deformation. Therefore, this paper uses SPH algorithm to study.

Using AUTODYN software to establish three-dimensional model is shown in Figure 1, the diameter of shaped charge(D) is 50 mm, the liner and explosive are smooth particles of SPH, the initiation mode is the center initiation. In this paper, the cone-shaped energetic liner and hemispherical liner are established respectively, in which the cone-shaped liner includes different cone angles and different thicknesses.

![Figure 1. Numerical simulation model.](image)

2.2. Material Model

PTFE/Al energetic material and 6061Al inert material were selected for the liner material, and both materials were described by Johnson-Cook strength model and Shock state equation [6]. Explosive material B was selected and described by JWL state equation [6], Material parameters are shown in Tables 1-2.

| Material | ρ (g/cm³) | A (MPa) | B (MPa) | n | C | C_0 (m/s) | S | γ |
|----------|-----------|---------|---------|---|---|-----------|---|---|
| PTFE/Al  | 2.44      | 11.02   | 75.94   | 1.01 | 0.16 | 1350 | 1.48 | 0.75 |
| 6061Al   | 2.70      | 265     | 426     | 0.34 | 0.02 | 5240 | 1.40 | 1.97 |

| A (Mbar) | B (Mbar) | R_1 | R_2 | ω | D_{c-j} (m/s) | E (GJ/m³) | P_{c-j} (GPa) |
|----------|----------|-----|-----|----|----------------|------------|---------------|
| 5.242    | 0.0768   | 4.2 | 1.1 | 0.34 | 7980           | 8.5        | 29.5          |

3. Results and Discussion

3.1. Difference analysis of energetic jet and inert jet

Figure 2 shows the numerical simulation results of jet forming process of PTFE/Al liner and 6061Al liner with cone angle 60° and 0.08D thickness.
It can be seen from Figure 2 that the time required for PTFE/Al energetic jet and Al inert jet to reach the same position is almost the same. This is because the density of the two liners is relatively close, so when the charge structure is the same, the head velocity of the jet formed by the liners of two different materials is not much different. But it is obvious that the morphology of the two jets is obviously different. With the extension of time, the head of PTFE/Al jet expands and diverges continuously, and the diameter increases continuously, showing the characteristics of non-condensation. However, the Al jet continues to elongate and thin, when the jet head reaches three times the explosion height, the jet appears a certain diameter shrinkage and fracture phenomenon, but the jet is still condensed.

Figure 3 shows the density distribution of the two kinds of jets at three times the burst height. It can be seen that for PTFE/Al jets, the density of the jet decreases obviously due to the continuous divergence of the jet. When the jet head reaches three times the explosion height, the density of the jet at different positions almost drops below 2.2g/cm³, and the density of the jet head drops around 1.2g/cm³. For the Al jet, the density at different positions of the jet is almost greater than 2.6 g/cm³ due to the relatively condensed jet.

3.2. Effect of Shape of Liner on Jet Forming

Figure 4 shows the jet forming process of conical liner (cone angle 60°, 0.12D thickness) and hemispherical liner.
It can be seen from Figure 4 that the cone shaped charge liner forms a pestle body with a certain length, while the hemispherical shaped charge liner forms almost no pestle body. The shaped charge liner is basically transformed into a jet with a large diameter. This is due to two different shapes of liner jet forming mechanism. However, when the jet reaches the same position, the time required for the jet formed by the conical liner is shorter, that is, the jet velocity formed by the conical liner is greater than that of the hemispherical liner, which is more conducive to avoiding the chemical reaction of energetic jet before penetrating the target and affecting the damage effect.

3.3. Effect of Cone Angle on Jet Forming

Figure 5 shows the jet forming process of energetic liner with different cone angles (0.12D thickness).
The distribution of jet velocity with length when the jet head formed by the liner with different cone angles reaches twice the burst height is shown in Figure 6. The statistical data of jet at this position are shown in Table 3.

Table 3. Jet data of different cone angle liners.

| Angle | Head velocity (m/s) | Tail velocity (m/s) | Length of penetrator (mm) |
|-------|---------------------|---------------------|--------------------------|
| 45°   | 8363.6              | 734.85              | 139.0                    |
| 60°   | 7819.3              | 891.9               | 124.4                    |
| 75°   | 7164.2              | 1074.3              | 112.2                    |
| 90°   | 6984.8              | 1272.6              | 101.6                    |

With the increase of cone angle of liner, the velocity of jet tail increases from 734.85 m/s to 1272.6 m/s. Velocity of jet head decreased from 8363.6 m/s to 6984.8 m/s, length of penetrator decreased from 139 mm to 101.6 mm. When the liner cone angle is small, although the jet head velocity can reach a higher value, but it needs a higher charge length, so as to occupy more structural space. When the cone angle is large, the mass of the liner decreases, resulting in less energetic materials carried, thereby reducing the energy release of energetic jet in the penetration process. Based on the above analysis, within the scope of this study, the ideal cone angle of the liner should be 60°.

3.4. Influence of Liner Thickness on Jet Forming

Figure 7 shows the jet forming process of energetic liner with different thicknesses (cone angle 60°).
Jet forming process of energetic liner with different cone angles.

The distribution of jet velocity with length when the jet head formed by the liners with different thicknesses reaches twice the explosion height is shown in Figure 8. The statistical data of jet at this position are shown in Table 4.

Figure 8. Jet velocity distribution of different thickness liner.
Table 4. Jet data of different thickness liner.

| Thickness | Head velocity (m/s) | Tail velocity (m/s) | Length of penetrator (mm) |
|-----------|---------------------|---------------------|--------------------------|
| 0.04D     | 9825.5              | 1222.0              | 118.3                    |
| 0.08D     | 7514.4              | 1064.6              | 120.0                    |
| 0.12D     | 7819.3              | 891.4               | 124.2                    |
| 0.16D     | 7475.6              | 783.6               | 126.1                    |

With the increase of the liner thickness, the head velocity of the jet decreases from 9825.5m/s to 7475.6m/s, the tail velocity decreases from 1222.0m/s to 783.6m/s, and the penetration length increases from 118.3mm to 126.1mm. This is due to the increase of the thickness of the liner, the mass increases, and the driving force of the explosive on the liner is weakened, so the overall velocity of the penetrator decreases. When the liner thickness is thin, although the jet velocity is high, the jet dispersion effect is obvious, the jet density is low, the energetic material carried by the liner is low, and the jet energy is limited during penetration, which affects the deflagration damage effect of the jet to the target. However, when the liner thickness is thick, although the liner carries more energy, the overall velocity of the liner decreases, the penetration ability is weakened, which is not conducive to the jet entering into the target to release energy. The ideal thickness should be about 0.12D.

4. Conclusion

In this paper, the jet forming characteristics of PTFE/Al energetic liner are studied by using AUTODYN simulation software. The effects of liner material and structure on jet forming morphology and velocity distribution were studied by numerical simulation. The conclusion is as follows:

1. There are obvious differences in the morphology between energetic jet and inert jet. Due to the low sound velocity of energetic liner material, the jet will produce radial divergence effect in the flight process. However, the sound velocity of Al material is generally high, so the jet has good cohesiveness all the time.

2. The jet conversion rate of hemispherical liner is relatively high, and the cohesion is good, but the overall velocity of jet formation is lower than that of conical liner, which is not conducive to penetrating target.

3. With the increase of the cone angle, the velocity of the jet tail increases, the velocity of the jet head decreases, and the length of the penetrator decreases. Considering the cohesion and velocity, the ideal cone angle of the liner should be about 60°.

4. With the increase of the thickness of the liner, the mass of energetic material carried by the penetrator increases. The results show that the cohesion of jet increases, but the velocity of jet head and tail decreases, and the ideal thickness of liner is about 0.12D.

References

[1] BAKER EL, DANIELSAS, NGKW, et al. Barnie: a unitary demolition warhead [C] // Proceedings of the 19th International Symposium on Ballistics. Interlaken, Switzerland: International Ballistics Society, 2001: 569 -574.

[2] ANIELSAS, BAKEREL, DEFISHERSE, et al. BAM: large scale unitary demolition warheads [C] // Proceedings of the 23rd International Symposium on Ballistics. Tarragona, Spain: International Ballistics Society, 2007: 239-246.

[3] XIAO J G. Research on damage effects of multi-layered concrete targets impacted by explosively formed penetrator [D]. Beijing: Beijing Institute of Technology, 2016.

[4] WANG YZ, YUQB, ZHENG YF, et al. Formation and penetration of jets by shaped charges with reactive material liners [J]. Propellants, Explosives, Pyrotechnics, 2016, 41(4): 618 - 622.
[5] CHEN J, YIN JP, HAN YY, et al. Numerical simulation of low density particle jets formation based on SPH method [J]. Chinese Journal of Energetic Materials, 2017, 25(9):756 - 762.

[6] Jiang JW, Wang SY, Zhang M, et al. Modeling and simulation of JWL equation of state for reactive Al/PTFE mixture[J]. Journal of Beijing University of Technology, 2012, 21(2):150-156.