Advances in Intelligent Systems Research, volume 168
International Conference on Modeling, Analysis, Simulation Technologies and Applications (MASTA 2019)

Effect of Powder Liner's Density Distribution on Perforation Performance

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Keywords: Powder liner, Density distribution, Jet morphology, Velocity gradient, Penetration depth.

Abstract. In order to study the influence of the density distribution of the liner on the jet velocity gradient and the penetration performance, two numerical models of the typical density distribution of the powder liner were established. One is the uneven distribution of the axial density of the powder liner, and the other is the uneven distribution of circumferential density of the powder liner. The LS-DYNA software was used to calculate the multi-condition numerical values, and the shape, velocity gradient distribution and penetration depth of the jet are obtained. The jet velocity and the depth of the perforation are calculated and analyzed in combination with the quasi-steady theory of fluid mechanics and the virtual origin concept. The results show that the axial density of the powder liner has a certain increase on the jet shape and penetration depth. The density of the powder liner is unevenly distributed in the circumferential direction, and the jet has a tendency to deflect toward high density.

Introduction

As the core component of the shaped charge warhead, the powder liner is of concern for the quality and end effect of the jet under the explosive load. For example, delaying the breaking time of the jet [1], the petroleum perforating bullet has no corpus callosum and high penetration depth [2], increasing the mass ratio of the jet-type mask and increasing the driving ability of the powder liner. [3]. The design of the powder liner is close to the bottleneck, and the potential for excavation is small. Therefore, researchers at home and abroad have turned their attention to the application of new materials and new processes in the formation of the powder liner. The powder metallurgy liner is widely concerned because of its flexible material ratio, simple processing technology, high jet penetration depth and large pore surface area [4], and largely avoiding the phenomenon of plugging. However, the powder liner prepared by the pressing process generally has a problem of uneven density distribution in the axial/circumferential direction.

In this paper, based on the above background, the axial/circumferential density distribution of the powder liner is uneven. The LS-DYNA finite element analysis software was used to carry out numerical simulation research, in order to provide theoretical basis for the shape, velocity gradient and penetration performance of the jet caused by uneven density distribution of the powder liner, and to provide reference for other related research.

Theoretical Analysis

According to the Allison and Vitalit hypothesis [5], there is a virtual source as the starting point of all jets, the jet velocity is linearly distributed along the axis, and the velocity of the jet micro-element does not change during the motion [6]. Therefore, the calculation formula for the penetration depth of the jet is

$$P = V_j t_0 \left(\frac{V_0}{V_j}\right)^{(1+\gamma)/\gamma} - S \tag{1}$$

Where: P represents the penetration depth; V_j represents the jet velocity at the intersection of the projectile; V_0 represents the velocity of the jet head; t_0 represents the time from the virtual origin to the surface of the target; S represents the distance from the virtual origin to the surface of the target; $\gamma = \sqrt{\rho_T/\rho_j}$ Where ρ_T represents the density of target plate, ρ_j represents the density of jet. According to the theory of fluid mechanics, the sum of static force and dynamic pressure on both sides of the collision point during the penetration process is equal can obtain[7];

$$\frac{1}{2}\rho_j\left(V_j - U\right)^2 = \frac{1}{2}\rho_t U^2. \tag{2}$$

The formula for the velocity of the jet that can be obtained by equating it with the above formula is:

$$U = \frac{V_0^{1+\gamma} t_0^{\gamma}}{(1+\gamma)[P(t)+S]^{\gamma}} \ . \tag{3}$$

It can be seen from the above formula that the jet velocity and the penetration depth of the jet are affected by the distribution of the powder liner when determining the projectile shell material and the target material. Therefore, in this paper, the ANSYS finite element simulation is used to further determine the influence of the density of the powder liner on perforation performance.

Simulation Model

Model and Working Condition Settings of the Powder Liner

The finite model includes air, HMX explosives, W-Cu powder alloy liners, 45# steel cartridge cases and 45# steel target plates. The perforating projectile structure, charge and explosive high (3.5cm) of each working condition are the same. Except for the control group, the powder liner was divided into three parts, and the density of each part was different, but the total mass of the powder liner was ensured to be the same. The specific working conditions and the model of the powder liner are shown in Table 1. The model of the powder liner material was selected from the Johnson-cook model and the Gruneisen equation of state commonly used in the explosion. The specific parameters are shown in Table 2 and Table 3. Because of the high strain rate and large deformation during the collapse process, the ALE algorithm is adopted to define the ALE multi-material group by the *ALE_MULTI-MATERIAL_GROUP keyword. For working condition 2 and working condition 3, the three-part powder liner is defined as a part-set by the keyword *SET_PART_LIST.

Table 1. Setting of simulated working conditions and the powder liner model

Control Group (Uniform Distribution of Powder Liner Density)		Axial Density Distribution is Uneven		Distribution of Circumferential Density is Uneven	
Simulation Model	Working Condition 1 Density（g/cm³）	Simulation Model	Working Condition 2 Density（g/cm³）	Simulation Model	Working Condition 3density（g/cm³）
	12.87		10.94 12.87 14.80		10.94 12.87 14.80

Table 2. JOHNSON_COOK constitutive equation

RO	G	n	m	C	D1	D2	D3	D4	D5
12.87	0.509	0.31	1.09	0.25	0	0	0	0	0

Table 3. EOS_GRUNEISEN equation of state

C	S1	S2	S3	GAMA	A	E0	V0
0.394	1.49	0	0	1.99	0	0	1

Modeling and Discretization of Shaped Charge System

This paper uses the Truegrid software for system modeling and structured grid generation. The unit system adopts cm-g-us. Since the working condition 1 and the working condition 2 are axisymmetrical structures, the 1/4 model estab is adopted, and the working condition 3 is a non-symmetric structure, so the full model is established. The model of the shaped charge system for each working condition is shown in Fig. 1.

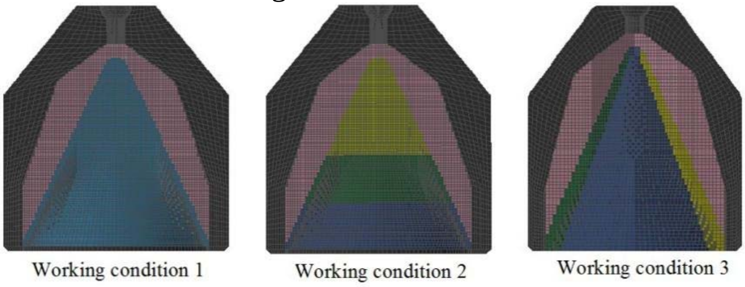


Figure 1. The model of the shaped charge system for each working condition

Simulation Results Analysis

Based on the fracture time of the jet in working condition 1, the calculation time of the other two working conditions is defined to this point, and the relative relationship between the jet and the penetration depth of the three working conditions is calculated according to equations (1) and (2). So as to analyze the influence of the density distribution of the powder liner on the shape, velocity and penetration depth of the jet.

Jet Velocity Distribution

The jet velocity distribution not only affects the quality of the jet, but also affects the penetration depth of the jet. Therefore, this section mainly analyzes the jet shape and jet velocity of the three working conditions, and takes the fracture time of the jet in the working condition 1 as the calculation termination time to analyze the influence of the density distribution of the powder liner on the quality of the jet.

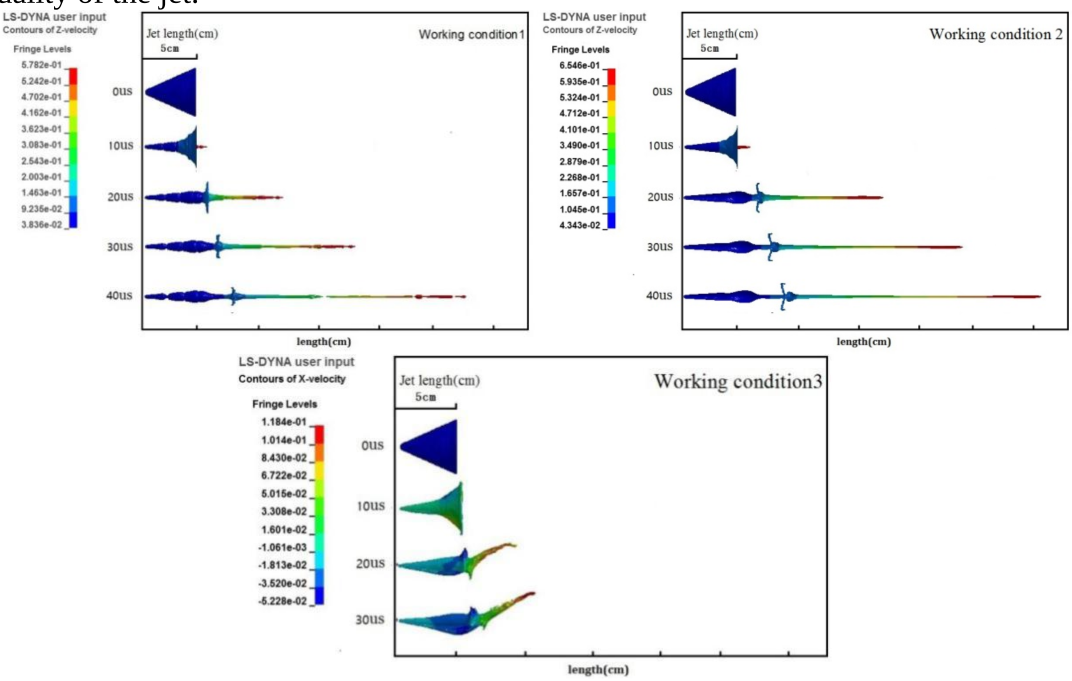


Figure 2. The jet shape and velocity distribution in each working condition

Fig. 2 is a cloud diagram of the jet velocity distribution in each working condition. Comparing the jet patterns in Fig. 2(a) and (c), it can be seen that the working condition 1 has a diameter shrinkage phenomenon at the jet body and the middle of the jet at 30 us, and the middle part of the jet is pulled off at 40 us, and the quality of the jet is not good. In the whole process of free stretching, the jet of working condition 2 has a good shaft diameter consistency, and the jet velocity gradient is reasonable, which can keep the jet shaft diameter change smoothly along the axis, and there is no phenomenon of jet diameter shrinkage during the whole stretching process. The jet quality is higher. In the working condition 3 jet calculation results (Fig. 2c), the jet is in the initial pressure state, the low-density region is first responded to the compression state, and the jet head is initially stretched; the three density materials respond in turn, which finally causes the jet to deflect toward the high-density powder liner from the Z-axis direction to the X-axis direction. The jet head is not uniform, and the dispersion phenomenon is obvious, which seriously affects the jet quality and after-effect performance. Therefore, the subsequent velocity gradient and penetration depth analysis is carried out only for Case 1 and Case 2.

Jet Head Velocity Attenuation Law

According to the jet formation mechanism, the outer surface of the powder liner forms a jet, and the inner surface forms a slug. During the jet stretching process, the inner surface metal material is continuously filled to the jet head to form a high-speed, high-pressure, high-temperature liquid fluid. The velocity reaches the peak value at this moment, and then it is replaced by the subsequent filler, the velocity gradually decreases, and a velocity gradient is formed with the new jet head of filling area, and in the jet stretching process, its position in the jet section is continuously moving backward along the central axis of the powder liner, at the next moment, there are also subsequent metal filling to the jet head, repeating the above process. Therefore, in order to facilitate comparison, this paper only compares the head velocity variation law at the initial jet, and studies the influence of density distribution of the powder liner on the jet head velocity.

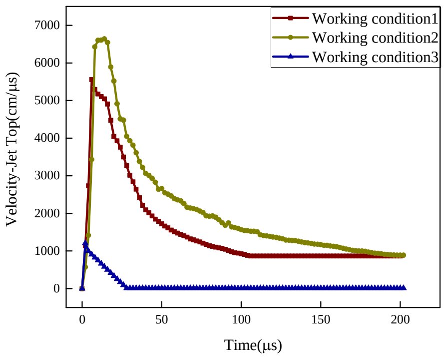
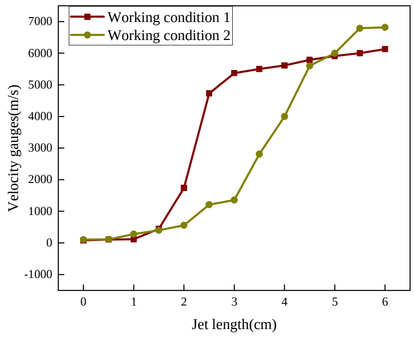


Figure 3. The variation of jet head velocity

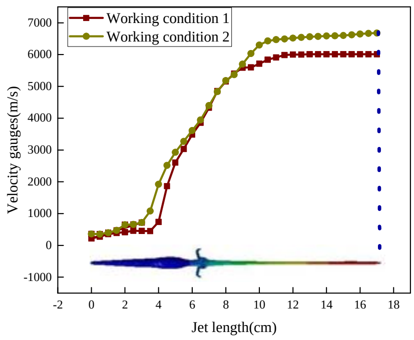
As can be seen from Fig. 3, the powder liner with high density at the top responds quickly to the explosive load, therefore, in the initial stage of the jet, the rate at which the jet head velocity in working condition 1 and working condition 3 increases to the maximum value is greater than that in working condition 2. However, when the velocity reaches the maximum, the metal at the top of the powder liner moves in the opposite direction of the jet velocity, and the velocity begins to decay. According to Fig. 2 (c), the direction of jet in working condition 3 deflected from z-axis to X-axis, and after 30us, the z-axis velocity decreases to 0.

Jet Velocity Gradient Distribution

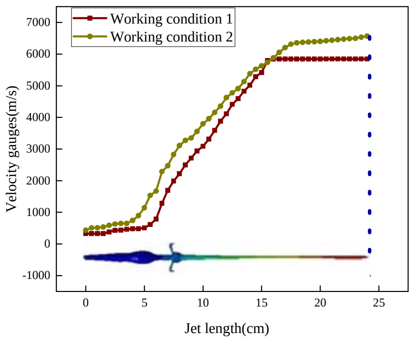
Fig. 4(a)~(d) is the jet velocity gradient distribution law at each time of working condition 1 and working condition 2. The length of the abscissa is 0, which represents the tail of the shaped charge jet. Starting from the tail of the slug, an observation point is set every 0.5mm to measure the velocity gradient distribution of the jet. The front part of the jet is the main part that penetrates the target plate. The slug has a pulling effect on the jet, which does not play a positive role in the jet piercing. When the difference between the slug and the jet velocity is too large, the jet will break off and the penetrating depth of the jet will be affected.



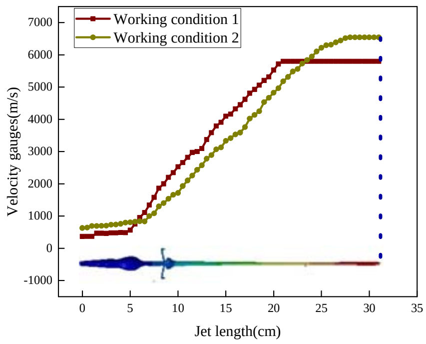
(a)10us



(b)20us



(c)30us



(d)40us

Figure 4. Flow velocity gradient distribution at each moment

Since the density in the top of powder liner in working condition 2 is lower than that in working condition 1, it is shown in Fig. 4(a) that the jet velocity gradient of the working condition 1 is greater than the working condition 2 under the same explosive load. As the shock wave propagates, forcing the powder liner along the axial direction of wall thickness, the density of the powder liner in the working condition 2 is gradually increased, leading to a gradual increase in the jet velocity gradient of the working condition 2. At 20 us, the jet velocity growth rate is equal to that in working condition 1, and exceeds that in working condition 1 at 30 us (as shown in Fig. 4a and c). It can be seen from Fig. 2(a) that the jet length in working condition 1 is less than that in working condition 2 when the jet at 40 us. In order to equally divide the jet speed within a limited length, the growth trend of the velocity in working condition 1 is greater than that in working condition 2(as shown in Fig. 4d).

Jet Penetration Depth

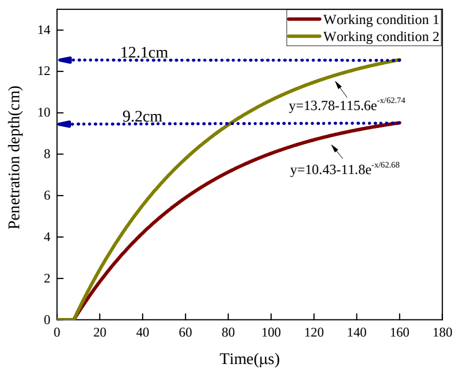


Figure 5. Jet penetration depth

In the process of jet formation, the jet head is formed at the top of the liner, and the jet tail is formed at the mouth of the liner. Under the same explosive load, the jet velocity gradient of the working condition 2 is larger, the jet stretch length is longer, and combined with the calculation formula of jet penetration depth, the jet penetration depth is also large; by comparison, the head speed of the jet 1 is significantly lower (as shown in Fig. 5).

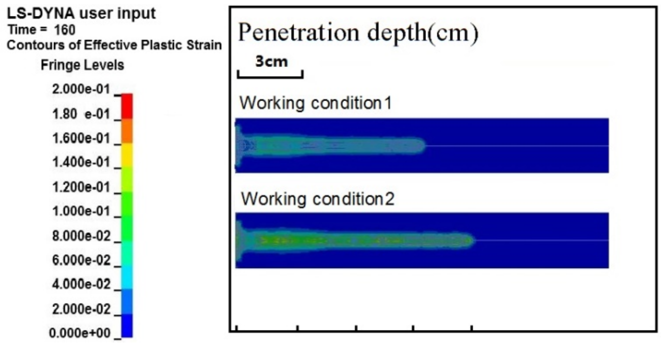


Figure 6. Hole strain rate cloud map

When a high-speed jet penetrates on the target plate, a high-intensity stress field is established near the interface between the jet and the target plate. Its strength is generally 1 to 2 orders of magnitude higher than the strength of the target material. The high-intensity stress field on the one hand erodes the jet head and on the other hand rapidly deforms the target material near the contact surface. A portion of the target material that is squeezed out of the pit flows out with the erosion jet, and another portion of the material surrounding the extruded channel remains in the tunnel. Therefore, after the jet penetration process is cut off, there is residual stress and strain near the inner wall of the perforation tunnel (fig. 6).

Conclusion

In this paper, LS-DYNA software is used to simulate the uneven distribution of density of the liner, and the quality and penetration depth of the jet are analyzed, and the following conclusions are obtained:

(1) Compared with the uniform density of the liner, the axial density increases from the top of the liner to the mouth of the liner, the fracture time of the jet is delayed, the quality of the jet is better, the velocity is evenly distributed along the jet, and the velocity of the jet head is larger (6630m/s).

(2) When the distribution of the phase density in liner is uneven, the deflection of the jet to the direction of the high-density liner is from the direction of Z axis to the direction of X axis, and the head of the jet is asymmetrical, with obvious dispersion phenomenon, which seriously affects the quality and after-effect performance of the jet.

(3) Compared with the uniform density liner, the penetration depth of the jet is greater (12.1 cm) when the axial density increases from the top of the liner to the mouth of the liner.

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