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To cite this article: Y J Wang *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **164** 012020

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# Study on formation of JPC under large standoff distance condition

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**Abstract.** In order to achieve penetration damage efficiently under larger standoff distance condition, a shaped charge warhead is designed on the basis of jetting penetrator charges (JPC) formation and disruption theory. The paper analyses the formation, elongation and disruption processes of JPC by using LS-DYNA software. The results show that JPC tail begins to break away at 8.5 charge diameters (CD) standoff distance. When the standoff increases, JPC head velocity decrease while JPC tail increase, and JPC length-diameter ratio increased significantly. Based on numerical simulation and theoretical investigation, it was found that the JPC still has good penetration ability at 15.5CD standoff distance, and JPC effective standoff is able to reach 20CD distance. The result provides a reference for the design of JPC warhead at large standoff distance.

## 1. Introduction

Modern armor protects against the shaped charge jet penetration, of which defeat mechanisms are both breaking the jet up on impact and altering the standoff. The penetration capability and stability are affected, because the jet is easily broken, especially at large standoff distance. Therefore, increasing the effective standoff has great significance on defeating remote target. Jetting Projectile Charge (JPC) [1] has a good penetration capability and a strong adjustability, which has good application prospect for dealing with some warheads aiming to defeat targets in large standoff distance. Aiming at improving penetration capability of warheads in large standoff conditions, Frueh and Heine [2] obtained velocity-distance information about the majority of the particles of two types of small-scale laboratory shaped charge at large standoff distance by using a combined technique of flash X-rays and high speed video cameras. Mayseless et al. [3] presented a new stochastic model to describe adequately the spread in the penetration data at short and long standoffs. Huang et al. [4] analyzed the structure of liner under large standoff distance condition, combining theoretical investigation and experimental verification. Based on JPC design method, Zhang et al. [5] designed three typical liner JPCs, and verified the penetration experiments—the penetration performance of JPC with spherical segment liner is the best. Subsequently, Fu et al. [6] and other researchers studied kinds of typical liner to analyze influence of liner parameters on penetration capability of JPC, and conducted experiments to verify the penetration capability under the condition of large standoff. Nowadays most scholars have focused on the mechanism of liner collapse and distortion and analysis of influencing factors about JPC penetration. However, for the large standoff distance, the influence of standoff distance on the JPC formation has not been reached at home and abroad.



In this paper, a shaped charge warhead is designed, having good penetration capability at large standoff distance, on the basis of JPC formation and disruption theory. The numerical simulation is carried out using dynamic finite element program of LS-DYNA for the influence of standoff distance on the JPC formation. Furthermore, the penetration capability of JPC is verified at the large standoff distance from the comparison of the simulation solution and the theoretical calculation.

## 2. Structure model and numerical simulation scheme

### 2.1. Design of structure model

Upon detonation of the shaped charge, the detonation wave, pushed by the rapidly expanding gaseous products along the axis of symmetry, contains higher pressures than the ultimate stress in the material, which allows us to model the material as an inviscid fluid. The jet of material forms, the tip of which moves at high velocity toward the target. And the remaining liner material is formed into a slug which follows the jet at a much lower velocity. The projectile will progressively stretch until it breaks up into small fragments.

The model assumes that equation, based on Zheng's [7] theoretical investigation on the necking and breaking up of a free metal in air produced by shaped charge, applied for describing relation of necking time and liner parameters in this unsteady process. The results are as follows:

$$t_{b1} = C_1 \left( \frac{\Omega \rho_j}{\sigma} \right)^{1/3} \quad (1)$$

$$t_{b2} = C_2(\phi) \left( \frac{\Omega \rho_j}{\sigma} \right)^{1/3} \quad (2)$$

where  $\Omega = \frac{1}{\pi \rho_j} \cdot \frac{dm}{dv_j} = r_0^2 t^*$ , and  $t_{b1}$  is jet necking time;  $t_{b2}$  is jet breaking time;  $1/t^*$  is jet initial

velocity gradient;  $r_0$  is jet initial radius;  $v_j$  is jet velocity;  $\rho_j$  is jet density;  $\rho_0$  is unperturbed density of the air;  $m$  is jet quality;  $C$  is speed of sound in undisturbed air, an independent normal constant without  $\Omega$ ,  $\rho_j$ ,  $\sigma$  etc.;  $\alpha$  is a constant relating to jet and liner materials;  $\sigma$  is flow stress or yield strength;  $C_2(\phi)$  is reduction of material area;  $\phi$  is related functions.

Applying the above equation to analysis the method of postponing jet breaking time and improving the stability of jet, it is required that the liner material has good plastic performance and the speed of sound with  $\rho_j$  as large as possible and  $\sigma$  as small as possible on process of liner selecting and machining. Secondly, it is required that the jet quality is as much as possible to reduce jet velocity and to improve  $\Omega$  on process of liner structural designing.

Considering above factors, the configuration of the liner in a shaped charge is sub-hemispherical and the initiation method is single-point initiation with wave-shaper. After analysing effects of shaped charge structure parameters with the help of numerical simulation, the final designed warhead, of which charge diameter was taken as 110mm, has good penetration ability at large standoff distance. A shaped charge is constructed from a robust casing filled with a cylindrical high explosive and a wave-shaper. At one end of the casing there is an axis-symmetric geometric shape precisely indented in the high explosive in which a liner is inlaid. The structure of shaped charge warhead in this paper is shown in Figure 1.

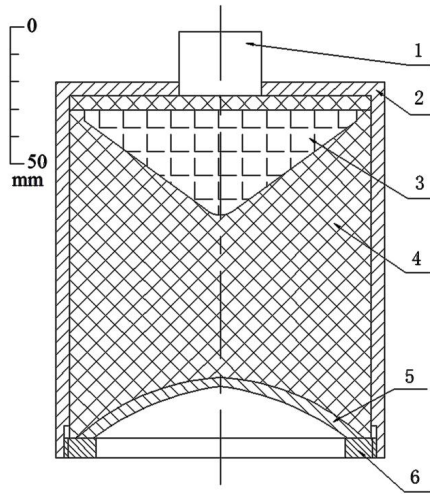


**Figure 1.** Structure of shaped charge warhead. (where 1 is the detonation device; 2 is the body shell; 3 is the wave-shaper; 4 is the explosive; 5 is the sub-hemisphere liner; 6 is the fixed ring.).

## 2.2. Establishment of the simulation model

The ALE algorithm provides the coupling mechanism between ALE fluid and Lagrange nodes. To solve the problem of large deformation, ALE algorithm can be used to calculate the JPC formation process, of which the explosive, liner, wave-shaper and air are meshed as ALE fluid, and the shell is meshed as Lagrange nodes. Due to symmetry, the model 1/4 of the geometry is enough. The symmetrical inhibit condition is added to the symmetrical surface of the model to restrict the node's displacement and rotation degrees of freedom. And the outflow boundary conditions of pressure are put in the boundary nodes in order to avoid the reflection of pressure at the boundary. The simulation model is shown in Figure 2.



**Figure 2.** Simulation model.

The processes of the liner collapse and shell crack generate high temperatures and pressures. The responses of liner material at different pressure levels are shown by both the Johnson-Cook material model and the Gruneisen equation of state. John-Cook's formulation of the flow stress is

$$\sigma_y = (A + B\bar{\epsilon}^{p^n}) [1 + C \ln \dot{\epsilon}^*] (1 - T^{*m}) \quad (3)$$

where  $A$ ,  $B$ ,  $C$ ,  $n$  and  $M$  are material constants;  $\bar{\epsilon}^p$  is the effective plastic strain;  $\dot{\epsilon}^*$  is the effective plastic strain rate,  $\dot{\epsilon}_0 = 1s^{-1}$ ;  $T^*$  is the relative temperature given by  $T^* = (T - T_{room}) / (T_{melt} - T_{room})$ .

The Gruneisen equation of state takes the pressure of compressible materials as

$$p = \frac{\rho_0 C^2 \mu [1 + (1 - \frac{\gamma_0}{2}) \mu - \frac{a}{2} \mu^2]}{[1 - (S_1 - 1) \mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2}]} + (\gamma_0 + \alpha \mu) E \quad (4)$$

where  $s$  is shock;  $p$  is particle;  $\rho_0$  is density of material;  $E$  is internal energy of initial unit volume material;  $C$  is interception at the vertical axis of the shock velocity versus particle velocity ( $u_s-u_p$ ) curve;  $S_1, S_2, S_3$  are the coefficients that determine the shape of ( $u_s-u_p$ ) curve;  $\gamma_0$  is Gruneisen gamma;  $a$  is the first order volume correction to  $\gamma_0$ .

The shaped-charge explosive is 8701, which is described by the “Mat\_High\_Explosive\_Burn” material option in DYNA and the JWL equation of state. The explosive burning equation describes the explosive behavior before its detonation, and controls the release of chemical energy for simulating detonation. The JWL equation describes the pressure, volume and energy of the reaction product in the process of detonation, it defines the pressure as

$$P = A(1 - \frac{\omega}{R_1 V}) \exp(-R_1 V) + B(1 - \frac{\omega}{R_2 V}) \exp(-R_2 V) + \frac{\omega E}{V} \quad (5)$$

where  $A, B, R_1, R_2, \omega$  are all constants,  $E$  is the initial internal energy; and  $V$  is the relative volume.

The wave-shaper is, which is described by the “Mat\_High\_Explosive\_Burn” material model and the Gruneisen equation of state. The Null material and the Gruneisen equation of state is used for the air as an ideal gas. The parameters of material models used in the calculations are to be found in Li et al. [8].

### 3. Influence of the standoff distance

The standoff of a shaped charge is the distance from the base of the liner or cavity to the target. It is known that the standoff in shaped charges has an optimum distance for best penetration performance. On one hand, the increase of standoff distance will make the JPC more fully stretched, which is beneficial to the penetration. On the other hand, “too-large” standoff distance will lead to the JPC break and affect the penetration seriously. Calculating numerical simulation models to present the influence of different standoff distance on JPC. Figure 3 is the image of liner collapse and subsequent projectile formation.

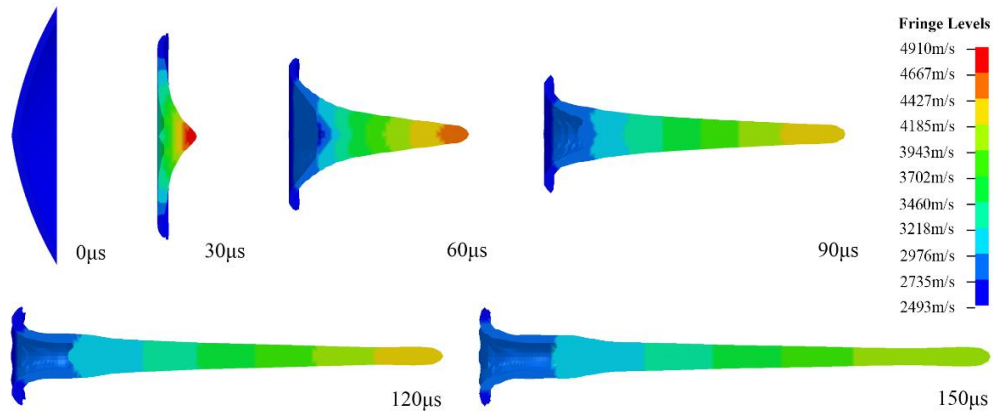


**Figure 3.** Image of the stages of formation of JPC.

Due to disturbance of wave-shaper, detonation wave is changed with instantaneous angle between the moving walls of the liner increasing. Detonation wave collapses and distorts the liner on its central axis, driving it into a JPC with the tip traveling at around 3~5 km/s. The boundary between jet and slug is not evident as a result of instantaneous angle and liner mass increasing, thus increasing the efficiency of the liner. This is achieved by using the sub-hemisphere liner and the wave-shaper, producing a larger-length-diameter-ratio, slower, uniform-distributable, more stable projectile.

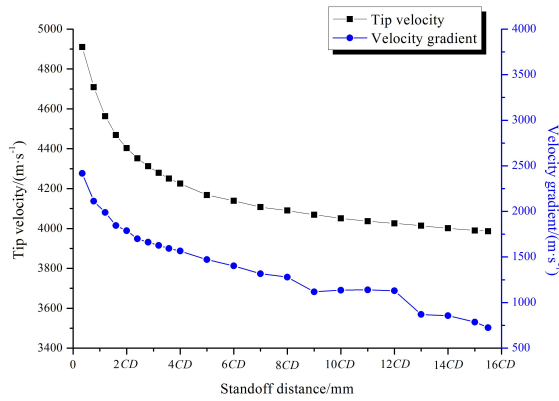


**Figure 4.** The change curves of velocity at different standoff distance.

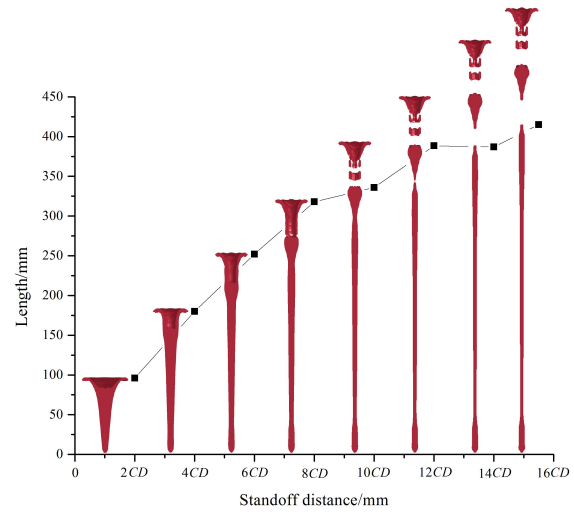


**Figure 5.** The change curve of length at different standoff distance.

The curve in Figure 4 shows the predicted JPC tip velocity rapidly increases to 4910m/s upon detonation of the shaped charge, and gradually decreases after a brief increase, subsequently stabilize at 4000m/s. But velocity gradient gradually decreases with time increasing. This process is conducive to maintain stable flight of JPC at a large standoff distance. Figure 5 shows that JPC stretches with necking and breaking up similar to the condition of jet at large standoff distance, even if the boundary between jet and slug is not evident. The particulates from broken tail of JPC, whose velocity is gradually decrease, are difficult to defeat the target.

**Table 1.** Formation parameters of JPC at different standoff distance.

| Standoff | Tip velocity<br>(m·s <sup>-1</sup> ) | Tail velocity<br>(m·s <sup>-1</sup> ) | Velocity gradient<br>(m·s <sup>-1</sup> ) | Length<br>(mm) | L/D  |
|----------|--------------------------------------|---------------------------------------|-------------------------------------------|----------------|------|
| 2.0CD    | 4403                                 | 2615                                  | 1788                                      | 96             | 1.6  |
| 4.0CD    | 4225                                 | 2660                                  | 1565                                      | 180            | 4.1  |
| 6.0CD    | 4139                                 | 2737                                  | 1402                                      | 252            | 6.4  |
| 8.0CD    | 4090                                 | 2811                                  | 1279                                      | 318            | 8.0  |
| 10.0CD   | 4051                                 | 2915                                  | 1136                                      | 336            | 17.0 |
| 12.0CD   | 4026                                 | 2897                                  | 1129                                      | 389            | 19.6 |
| 14.0CD   | 4001                                 | 3145                                  | 856                                       | 387            | 48.9 |
| 15.5CD   | 3986                                 | 3261                                  | 725                                       | 416            | 52.3 |

The calculated results of JPC formation can be seen in Table 1 at the different standoff distance, and the standoff distance includes 4CD (Charge Diameter), 6CD, 8CD, 10CD, 12CD, 14CD, 15.5CD. When the standoff reaches 8.5CD, it is obvious that the standoff influences on JPC formation, and tail of JPC begins to breaking up. With raising standoff, the tip velocities and velocity gradient decrease, but tail velocity increases. Meanwhile, L/D (length-diameter ratio) significantly increases because of radius slimming and length elongating. The JPC has a lot of advantages, including high velocity, uniform velocity gradient, and large L/D, with strong penetration capability. Figure 6 shows that JPC still maintains the continuous body with tail breaking up at 15.5CD standoff distance. At this time the length of continuous partial JPC was 416mm whose tip velocity reached to 3986m/s. The JPC can defeat 4CD target according to experiences. Therefore, it can be concluded that JPC has good penetration capability at 15.5CD standoff distance.



**Figure 6.** Image of JPC formation at 15.5CD standoff distance.

Based on Chou and Flis assumptions [9], JPC initial strain ratio of each segment is regarded as constant, and then the velocity attenuation can be ignored. With taking the average diameter of JPC as the calculated diameter, JPC breaking time, JPC completely losing penetration capability, on the basis of dimensional analysis and hydrodynamic theory, could be expressed as

$$\bar{t}_b = 3.75 - 0.125\bar{\eta}_0 + \frac{1}{\bar{\eta}_0} \quad (6)$$

where  $\bar{t}_b$  is the dimensionless breaking time;  $\bar{\eta}_0$  is the dimensionless initial strain ratio.

Introduction of equation of initial strain ratio as

$$\bar{\eta}_0 = \eta_0 r_0 / C_p \quad (7)$$

where  $\eta_0$  is the initial strain ratio, depended upon the movement velocity ( $V_0$ ) and initial length ( $L_0$ ),

which  $\eta_0 = V_0 / L_0$ ;  $r_0$  is initial undisturbed radius;  $C_p = (Y / \rho_0)^{\frac{1}{2}} = 0.15 \text{ km/s}$  for copper liner.

Substitution of equation (7) for  $\bar{\eta}_0$  and we find

$$t_b = \frac{r_0}{C_p} \left( 3.75 - 0.125 \frac{\eta_0 r_0}{C_p} + \frac{C_p}{\eta_0 r_0} \right) \quad (8)$$

Taking the formation parameters of JPC simulation at 200 $\mu\text{s}$  to substitute for related parameters of equation (8), we can get the value of the breaking time. Furthermore, the effective standoff distance can be obtained by multiplying the breaking time with the movement velocity. When JPC flight exceeds effective standoff distance, it is difficult to defeat the target for JPC whose breaking up is serious. The Formation parameters of JPC are shown in Table 2.

**Table 2.** Formation parameters of JPC at 200 $\mu\text{s}$ .

| Length (mm) | Tip velocity (m·s <sup>-1</sup> ) | Tail velocity (m·s <sup>-1</sup> ) | Tip radius (mm) | Tail radius (mm) |
|-------------|-----------------------------------|------------------------------------|-----------------|------------------|
| 291         | 4107                              | 2790                               | 3.93            | 19.64            |

For the breaking time and the effective standoff distance, we take  $t_b = 536 \mu\text{s}$  and  $H = 2201.3 \text{ mm}$ . The effective standoff distance of the shaped charge warhead reaches 20CD.

#### 4. Conclusions

From the results of the simulation solution and the theoretical calculation studies presented in this paper the following conclusions may be drawn:

1. On the basis of the theory model of jet necking and breaking time as well as other related researches, a shaped charge warhead whose JPC has good penetration capability at large standoff distance was designed.
2. When the standoff reaches 8.5CD, it is obvious that the standoff influences on JPC formation, and tail of JPC begins to break up. With raising standoff, the tip velocities and velocity gradient decrease, but tail velocity increases. Meanwhile, L/D significantly increases because of radius slimming and length elongating.

3. The simulation concludes that JPC of the shaped charge warhead forming has good penetration capability at 15.5CD standoff distance. The effective standoff distance of the shaped charge warhead, on the basis of theoretical calculation, reaches 20CD.

### Acknowledgments

The work presented in this paper has been funded by the Graduate Research and Innovation Foundation of Jiangsu province under NO. SJZZ16\_0067.

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