Research on Jet Incoherence of Depleted Uranium Liner

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Abstract. Jet formation is the decisive factor of penetrating power of shaped charge, coherence and stability contribute to penetration. In the same condition, multiple penetrating tests of the shaped charge with depleted uranium(DU) liner did not get the expected results. In order to study the jet forming characteristics of DU liner under static explosion condition, an X-ray photography experiment was designed, which turned out to show the jet being badly incoherent. To research the incoherence of DU shaped charge jet from principles of jet incoherence, supersonic collision worked out to be the reasons for incoherence of the shaped charge jet. This paper provides a method for structural optimization of DU shaped charge and DU liner processing, which has guiding significance for application of DU liner in high explosive antitank projectile.

1. Introduction
Shaped charge warheads have shown unique advantages in the field of anti-tank technology. The liner is the core component of shaped charge, and its available material types and material properties have been widely concerned by domestic and foreign researchers [1]. According to the theory of constant incompressible ideal hydrodynamics, the penetration depth of the shaped charge jet is positively correlated with the density of the liner material, thus, to discover a better high-density metal for liner has become a new research hotspot [2-4]. However, it does not mean that the higher density of the material is better for liner considering the physical properties, chemical properties and economic benefits of the material.

Uranium in nature contains 99.275\% of U-238, 0.720\% of U-235 and 0.005\% of U-234. Depleted uranium, which has the advantages of high density, good mechanical properties, unique afterburning effect and reasonable price, is mainly composed of U-238 and small amounts of U-235 and U-234, and can be used for liner. Depleted uranium liner is usually alloyed with Vanadium, Titanium, Molybdenum, Zirconium, Niobium or other metals in order to improve the strength and toughness of depleted uranium materials. In this paper, we studied jet incoherence of Uranium-Niobium liner.

From the domestic and international papers published, studies on depleted uranium were mainly focused on its radioactivity and hazards and depleted uranium armor-piercing projectile [5]. Only Tie-Fu Wang et al [6-7] studied the effects of impurities and heat treatment process on the quality of the depleted uranium jet by static penetrating tests. Gong Bailin et al [8-9] studied the armor breaking performance and penetration aftereffects of depleted uranium alloy shaped charges by numerical simulation and static penetrating tests. However, little attention has been devoted to the jet forming of depleted uranium alloy liner, especially to jet incoherence. The incoherency of jet can greatly diminish...
the power of shaped charge, the cause of jet incoherence must be investigated, and jet incoherency must be suppressed. Therefore, to research incoherency of depleted uranium alloy jet is a necessary issue.

2. X-ray photography experiment for jet formation

2.1. Method

The X-ray photography test for jet forming of depleted uranium alloy liner was executed in the static explosion shelter, as shown in Figure 1, the assembled depleted uranium alloy shaped charge was placed on the PVC plastic support cylinder to make it in a suspended state. Along the axis of the liner, two X-ray cameras were set up on one side to take pictures of jet moving and stretching state at two different moments, and a camera film was set up on the other side to record the images of the metal jet. A 8# electric detonator was installed at the center of bottom of the shaped charge to detonate the warhead. Figure 2 illustrates the structure of shaped charge for the static explosion tests, and the explosive used for the tests was RDX-8701.

In order to exclude the possibility of DU liner jet being incidentally incoherent, X-ray photography experiments were performed on two shaped charges in the same state. Four different moments were recorded for two charges, \( t_1=30 \, \mu s \), \( t_2=40 \, \mu s \), \( t_3=55 \, \mu s \), and \( t_4=70 \, \mu s \), respectively, \( t_1 \) and \( t_4 \) were for the first charge, and \( t_2 \) and \( t_3 \) were for the second charge.

2.2. Result

The X-ray images of the jet of depleted uranium alloy liner were shown in Figure 3. At the moment of \( t_1=30 \, \mu s \), looking from the jet zone, the jet formed by depleted uranium alloy liner had a clear outline, and the slug and the jet could be easily distinguished, the lateral boundaries of the jet are clear, the head of the jet started to show slight incoherency. Looking from the slug zone, the slug remained a normal shape, reasonable length and moderate diameter, but its bilateral edges were blurred and surrounded by a small amount of depleted uranium alloy particles, looking from the collapse area, the collapse area is clearly outlined, and the cloud formed by depleted uranium metal particles occupied the whole ring-shaped collapse area. At the time of \( t_2=40 \, \mu s \), it could be seen that the bilateral edges of the jet were clear, and the jet head had been obviously split, the bilateral edges of the slug were blurred and accompanied by a few metal particles, the diameter of the middle of slug increased, compared with the slug state at \( t_1 \) of the first charge, the clarity of its profile and the density of metal clouds both decreased. At \( t_3=55 \, \mu s \), the clarity of jet decreased, and the head of jet was completely dispersed, both sides of slug became more blurred, the length of the slug was compressed, the outline of the collapse zone was further blurred and the density of metal clouds were further reduced on the basis of the
moment of $t_2$. At $t_4=70$ μs, the lateral edges of jet blurred, the bifurcation length of the jet was significantly increased and the head of jet showed a completely particulate state, and the diameter of the incoherent jet gradually increased along the axis to the right, the diameter of the middle part of the slug became significantly larger, the blurring of slug increased and the accompanying metal particles expand into small clouds of metal particles, the outline of the collapse zone is blurred, and a little metal particle clouds still existed inside it.

In general, the stretching length of the depleted uranium alloy jet increased with time accumulated, and the incoherent length of the jet increased as well. Meanwhile, the level of jet incoherence and jet granularity increased. The slug was continuously compressed so that the diameter of the middle part gradually became larger. The collapse zone gradually faded, and the density of depleted uranium metal particle clouds kept decreasing and gradually dissipated.

![Figure 3. X-ray images of DU alloys jet](image-url)
3. Analysis
The results of the X-ray photography tests confirmed the jet incoherence of the depleted uranium alloy liner in the structure, which can be explained in principles of jet incoherence.

In accordance with the constant incompressible ideal fluid theory, the liner is treated as an ideal non-viscous incompressible fluid. The detonation wave sweep to the side of the liner, which cause the liner collapsed. The metal splits into two parts of slug and jet after the metal collides at the axis. As shown in Figure 4, in the static coordinate system, the detonation wave whose speed is defined as $D$, drives the micro-element $P$ to the speed of $v_0$ suddenly, the micro-element $P$ reach the point $B$ finally, at which time the detonation wave sweep to $P'$. Liner is an axisymmetric object, $\alpha$ is half cone angle, $\beta$ is collapse angle, $C$ is the perpendicular foot of line $PA$ and line $BC$. As shown in Figure 5, the dynamic coordinate system fixed to the collision point $A$ travels at the speed of $v_1$. In the dynamic coordinate system, the micro-elements flow along the generatrix of the liner to the collision point $A$ at the speed of $v_2$, the metal is divided into two parts moving in opposite directions after crashing at the point $A$, jet flow to the right and slug flow to the left. In the dynamic coordinate system, the metal micro-elements flow to the collision point with the speed of $v_2$, and then, the metal micro-elements flow to the right with the speed of $v_3$ and to the left with the speed of $v_4$, respectively.

![Figure 4. Liner collapsing process in static coordinate system](image)

![Figure 5. Jet flowing in dynamic coordinate system](image)

In the theory of jet forming, the PER quasi-steady theory proposed by Pugh, Eichelberger, and Rostoker on the basis of the steady theory assumes that the collapse velocity of the metal gradually decreases from the top to the bottom of the liner. However, the assumption of equal velocity collapsing in the steady theory is convincing for the theoretical analysis in this paper to illustrate the jet incoherence of the DU liner, which is reflected in the study of jet incoherence by Ping Wu [10] and Yan Li et al [11].

In the steady theory, the coming flow formed by the micro-elements of the metal in the dynamic coordinate system separates into two metal flows after the collision at the point $A$. The velocities after separation are still equal to those before separation, i.e., $v_2=v_3$ and $v_2=v_4$. However, the fact is that pressure works in the process of the metal coming flow passing through the high-pressure zone at the collision point, so there must be $v_2>v_3$ and $v_2>v_4$. Based on the premise that the parameters of the coming flow passing the high-pressure zone at the collision point will change, Liu Jun et al [12] used two metal rods of infinite length and certain width to collide at a certain angle and speed to verify and refine the principles of jet incoherence proposed by Walker [13], and arrived at the following principles.

when $v_2<C_L$, the shaped charge jet is coherent and steady.
when $C_0<v_2<C_L$, the shaped charge jet may be incoherent or coherent, the jet formation is related to many factors such as the elasticity of metals, angle of collision, speed of collision, etc.
when $v_2>C_L$, the shaped charge jet is definitely incoherent.

In the principles above,

$$c_L = \sqrt{\frac{\beta(1-\gamma)(1+\gamma)}{\rho}} C_0, \quad c_0 = \sqrt{K/\rho}$$  \hspace{1cm} (1)
Where $C_L$ is the low pressure longitudinal sound speed for the material of liner, $C_0$ is the bulk sound speed for the material of liner, $\gamma$ is Poisson's ratio, $K$ is the bulk modulus, $\rho$ is the density of materials.

we can use the principles above to verify the jet incoherence of DU liner. In the following, we should derive the $v_2$ of jet first.

Kennedy discussed the classical Gurney formula in detail and derived the equation of the collapse velocity of open surface flat plate structures [14-15]

$$v_0 = \sqrt{\frac{2E}{\gamma+1}} \left[ \frac{(1+2\mu')}{6(1+\mu')^2} + \mu' \right]^{1/2}$$

where $\sqrt{\frac{2E}{\gamma+1}}$ is Gurney’s constant(mm/μs), $M$ is the mass of liner, $m$ is the mass of explosive.

Applying the sine theorem to the triangle $\Delta PAB$ in the static coordinate system in Figure 4 leads to the following conclusion

$$\frac{v_1}{\sin \theta} = \frac{v_0}{\sin \beta}$$

$\theta = 90^\circ - \frac{\beta - \alpha}{2}$

Applying the sine theorem to the triangle $\Delta PBP'$ arrives at the following conclusion

$$\frac{v_0}{\sin(\beta - \alpha)} = \frac{D}{\sin \alpha}$$

The micro-elements of liner, looked at the stationary point $A$ in the dynamic coordinate system in Figure 5, flow towards point $A$. Therefore, the following equation can be derived

$$v_2 = v_1 \cos \beta + v_0 \cos \theta$$

The relationship between $v_2$ and $v_0$ in the dynamic coordinate system can be derived by combining equations (3), (4) and (5)

$$v_2 = v_0 \left[ \frac{\cos \left( \frac{1}{2}(\beta - \alpha) \right)}{\tan \beta} + \sin \frac{\beta - \alpha}{2} \right]$$

Some of the relevant parameters of the depleted uranium alloys and the shaped charge are shown in Table 1 and Table 2.

| material | $\rho$/g·cm$^{-3}$ | $\gamma$ | $K$/GPa |
|----------|------------------|---------|---------|
| DU       | 19.05            | 0.20    | 97.9    |

| parameter | $\sqrt{\frac{2E}{\gamma+1}}$/mm·μs$^{-1}$ | $M$/g | $m$/g | $\alpha^\circ$ | $D$/mm·μs$^{-1}$ |
|-----------|---------------------------------------------|-------|-------|---------------|----------------|
| value     | 2.425                                       | 858   | 254   | 27.5          | 8.4            |

Substituting the above parameters into equations (1), (2) and (6) respectively, we can work out the $v_2$ for the jet of depleted uranium shaped charge designed in this paper in the dynamic coordinate system, where the relative coming velocity $v_2=4,701$ m/s, the bulk sound speed for the depleted uranium alloys is $C_0=2,267$ m/s, and the low pressure longitudinal sound speed for the depleted uranium alloys is $C_L=3,206$ m/s. Analyzing from the above results, we can work out the inequality $v_2>C_L$, which meets the principles of jet incoherence.

### 4. Conclusion

The X-ray photography tests for jet formation of shaped charge have confirmed the jet incoherence of the depleted uranium alloys liner. The jet incoherence was analyzed based on the principles of jet incoherence, and the following conclusions were drawn.

1) The bulk sound speed for the depleted uranium alloys is $C_0=2,267$ m/s, and the low pressure
The longitudinal sound speed for the depleted uranium alloys is $C_L=3,206$ m/s. When the depleted uranium alloys is applied to shaped charge liner, the relative coming velocity $v_2=4,701$ m/s in the dynamic coordinate system, thus, the inequality $v_2>C_L$ meets the principles of jet incoherence, causing the incoherent phenomenon of DU shaped charge jet.

2) When designing the shaped charge warheads with the depleted uranium alloys liner, it is necessary to reduce the jet incoherence in order to ensure the penetration power of the warheads. We can consider to increase the cone angle of the depleted uranium alloys liner to reduce the relative coming velocity $v_2$ when liner collapses, which can effectively suppress the jet incoherence of the DU alloys shaped charge.

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