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Investigation of Materials for Liners of Shaped Charge Warhead and Their Optimum Standoff Distances

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Abstract

Each specific shaped charge has its own optimum standoff distance. However, there is no solid research which reports on the analysis of this distance. This research attempts to determine the optimum standoff for a common shaped charge warhead so that the maximum jet penetration can be obtained. In addition, a series of numerical analyses varying materials for liners, i.e. copper, tantalum and tungsten, were conducted using an explicit finite element (FE) code, AUTODYN. The optimum standoff distance for each liner can be determined from the standoff-penetration chart presented in this paper. This study reveals that the optimum standoff distances for copper, tungsten and tantalum are 3.63D, 3.89D and 4.46D, respectively, where D is a cone diameter of shaped charge. The penetration depth for each standoff distance is in the same trend with the corresponding jet momentum except the copper liner detonated at 5D standoff where the high jet momentum leads to high radius of penetration.

1. Introduction

Shaped charge warhead is a cylinder of high explosive with hollow cavity at the end opposite to the initiation train. The cavity contains a liner made from metal, alloy, glass, ceramic, wood, and etc. The most common shape of liner is a conical shape as presented in Fig. 1. Shaped charge produces a hypervelocity jet of liner up to 6-10 km/s at the tip and 1-3 km/s at the tail [1]. This type of warhead is used in various applications such as metal cutting, anti-armour / anti-tank, and etc.

The performance of shaped charge depends on cone angle, material of liner, explosive type, and standoff distance between detonation point and target. In addition to these parameters, the performance of shaped charge also depends on the reliability of manufacturing processes, e.g. concentricity, consistency, homogeneity of the explosive filling [2].

The purpose of this study is to investigate the effects of liner material on the performance of jet penetration on an armour target at various standoff distances. In addition, this study aims to determine the optimum standoff distance for each liner material in which the deepest penetration can be obtained from the hypervelocity impact jet.

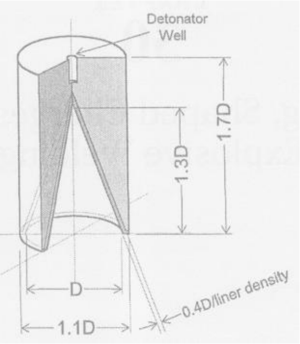

Fig. 1 Typical shaped charge [1]

2. Jet Formation and Penetration Model

2.1 Jet formation

The component of a shaped charge warhead that contributes to hypervelocity jet forming is the liner, as shown in Fig. 1. The liner is collapsed and accelerated at some small angle to the explosive liner interface when the detonation waves pass over the liner [1]. In the apex zone of liner, the charge per metal mass ratio (C/M) is quite high which consequently produces very high velocity of jet around that position. Other portions of the liner are squeezed-out at lower velocity compared to that of the liner near the apex zone because of lower C/M ratio. Fig. 2 shows that the front tip of jet moves forward with higher velocity whilst the rear jet moves at rather lower velocity. The front and rear jets are approximately 10%-20% of the liner where the rest is called slug which follows the jet at much lower velocity [3].

In some instances, the jet might break and spread out into a number of discrete particles, instead of a cohesive lump of jet, before reaching the target. This is called an incoherent jet. Kelly et al. [4] proposed an analytical model employed to predict an existence of incoherent shaped charge jet. A Mach number of jet (M_β) is employed to determine whether the jet is coherent or incoherent where M_β can be calculated using Eq. (1). The jet is coherent when the value of M_β is less than unity whilst it is an incoherent jet when the value of M_β is greater than or equal to unity.

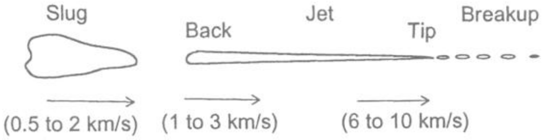

Fig. 2 Jet configuration [1]

$$M_\beta = \frac{V \cos \beta / 2}{c_0 \left[1 + \frac{(n-1)}{2} \left(\frac{V}{c_0} \right)^2 \sin^2 \beta / 2 \right]^{1/2}} \qquad (1)$$

where V= jet speed

β = liner collapse angle

c_0 = nominal bulk sound speed of liner

n = constant parameter for liner in Murnaghan equation of state

A further theory of jet formation and the calculation of velocities of jet and slug can be found in Pugh et al. [5].

2.2. Penetration model

Birkhoff et al. [6] developed a simple penetration model to determine the penetration depth resulted from the hypervelocity impact jet as presented in Eq. (2). The model was developed based on the Bernoulli theory with the assumptions listed below.

1.Both the jet and the target behave like ideal liquids.

2.The jet is travelling at a constant and uniform velocity.

3.The shape of the jet is in the form of a rod.

As the pressure of the jet far exceeds the yield strength of most target material, the strength of target and jet can be neglected in the model. It is noted in [7] that the strength of target material can be neglected when the jet velocity is above 2000 m/s.

$$P = l\left(\rho_j / \rho_T\right)^{1/2} \tag{2}$$

Where P= penetration depth

l = jet length

ρ_j = density of jet material

ρ_T = density of target material

However, there are several limitations in the simple penetration model [8] presented in Eq. (2). For example, the secondary penetration resulted from the residual inertial of the jet is not included in the model. Moreover, the model does not consider the effects of material strength, strain and strain rate dependency of the material. The variation in the penetration depths resulted from different standoff distances is not directly calculated by the simple model.

Pack and Evans [9] proposed a more sophisticated penetration model with taking into account of the target material strength as presented in Eq. (3).

$$P = \left(\frac{\rho_j}{\rho_t}\right)^{1/2} l \left(1 - \frac{\alpha Y}{\rho_j V^2}\right) \tag{3}$$

The term $\alpha Y/\rho_j V^2$ represents the reduction in penetration depth as a result of the target material strength.

The models presented in Eq. (2) and Eq. (3) do not consider whether the jet is formed in coherent or incoherent state. In addition, these models were derived based on the assumption that the velocity along the length of the jet is constant while the actual jet has top speed at the tip.

A summary of shaped charge jet penetration models can also be found in [8]. All of the analytical formulas employed to determine penetration depth presented in [8] require a jet length as one of input parameters. To the best of authors' knowledge, the jet length presented in [8] is previously known and equal to the length of a penetrator or projectile. Currently, however, there is no research reported on the calculation of the jet length. Therefore, a numerical method is more suitable so as to investigate the penetration depth resulted from a hypervelocity jet of a shaped charge warhead.

3. Numerical Models

2D axisymmetric models were analyzed using an explicit finite element (FE) code, AUTODYN, to investigate the behavior and performance of shaped charge warheads. A steel target represented an armor was placed next to the shaped charge warhead so that the squeezed jet will penetrate the armor. In this research, the armor was at distance of 2D, 3D, 3.5D, 5D and 7D in each analysis where D is the cone diameter of warhead. These distances were varied so as to investigate an optimum standoff distance where the jet reaches a maximum penetration depth.

The configuration of the FE model of shaped charge warhead investigated in this research is presented in Fig. 3. The 2D modeled warhead was revolved 270° in order to present the compositions of shaped charge warhead. Euler meshes were employed to model the explosive, air, liner and target armor while the warhead casing was modeled using Lagrange meshes.

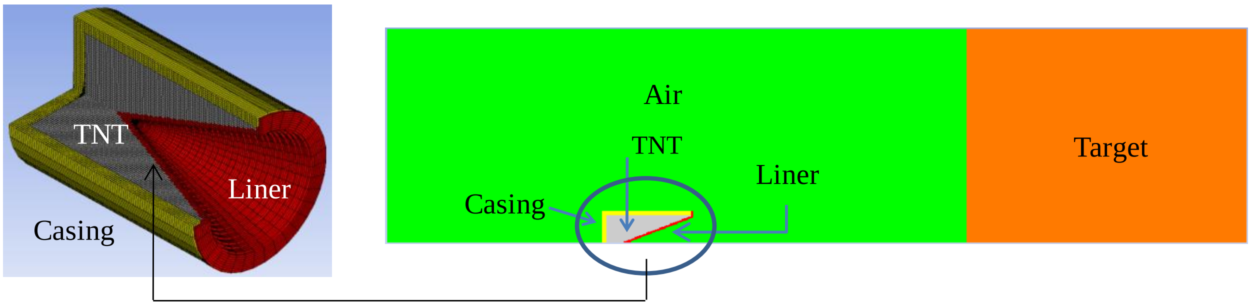

Fig. 3 Description of the 2D axisymmetric FE model of shaped charge warhead and surrounded domain

3.1 Material properties

High strength and high toughness steel in AUTODYN material library was selected to model the target armor in the FE models. Their material properties are listed in Table 1. In order to investigate the penetration capability of each material for liner, three types of materials were modeled and analyzed. Common materials for liner are copper, tantalum and tungsten. They are all investigated in this research. These materials were modeled using the Steinberg Guinan strength model [10]. The material parameters for each strength model obtained from the default values in AUTODYN material library are listed in Table 2. The properties and equation of state (EOS) of air in the FE model are presented in Table 3.

Table 1 Material properties of steel armor

Shear modulus, kPa	8.18×10^{7}
Yield stress, kPa	1.539×10^{6}
Hardening constant, kPa	4.77×10^{5}
Hardening exponent	0.18
Strain rate constant	0.012
Thermal softening exponent	1
Melting temperature, K	1.763×10^{3}
Reference strain rate. /s	1

Table 2 Material properties of copper, tantalum and tungsten

	Copper	Tantalum	Tungsten
Density, g/cm^{3}	8.93	16.69	19.3
Shear modulus, kPa	4.77×10^{7}	6.9×10^{7}	1.6×10^{8}
Yield stress, kPa	1.2×10^{5}	7.7×10^{5}	2.2×10^{6}
Maximum yield stress, kPa	6.4×10^{5}	1.1×10^{6}	4×10^{6}
Hardening constant	36	10	7.7
Hardening exponent	0.45	0.1	0.13
Derivative dG/dP	1.35	1.001	1.501
Derivative dG/dT, kPa/K	-1.8×10^{4}	-8.97×10^{3}	-2.21×10^{4}
Derivative dY/dP	0.003396	0.01117	0.02064
Melting temperature, K	1.79×10^{3}	4.34×10^{3}	4.52×10^{3}

Table 3 Material properties of air in the FE model

Density, g/cm3	0.001225
Gamma	1.4
Reference temperature, K	288.2
Specific heat, J/mKs	717.60

3.2 Analysis results

Fig. 4 and Fig. 5 show shapes and velocity contours of the simulated jets varying materials and standoff distances. They were captured just before reaching the target armor. As the penetration capability depends on the density and jet velocity, therefore, momentum of jet is the main parameter to indicate the performance of jet penetration. Fig. 6 presents the jet momentum obtained from all analysis cases conducted in this research. It can be seen from Fig. 6 that the jet generated from the copper liner has highest momentum in all analysis cases; following by tantalum and tungsten liners, respectively.

The depth of penetration into steel armor resulted from copper, tantalum and tungsten liners obtained from the FE analyses are plotted versus the standoff distance in Fig. 7. The jet from a copper liner produces the highest penetration depth for all standoff distances, except at 5D standoff distance where the tantalum jet produces the deepest penetration. This result contradicts to the jet momentum of copper and tantalum, in which the copper liner generates the highest momentum. However, the radius of penetration produced by the copper jet is 48 mm, which is larger than 36 mm produced by the tantalum jet. Therefore, the jet momentum indicates the penetration performance in both penetration depth and radius of penetration in the target armor. It is noted that the penetration depth and radius of penetration reported in this study were obtained from the FE analyses.

The penetration depths were fitted using a 3rd degree polynomial approach and also presented in Fig. 7. The optimum standoff distance and the corresponding penetration depth for each liner material from the fitted curve are listed in Table 4.

The momentum curves of tantalum and tungsten jets correlate well with their corresponding penetration curves. The momentums of tantalum jets are higher than those of tungsten jets in all analyses with various standoff distances. These results claim the deeper penetration depths resulted from the tantalum jets compared to those of tungsten jets as shown in Fig. 7.

From Fig. 7 and Table 4, the optimum standoff distances are 3.63D, 3.89D and 4.46D for copper, tungsten, and tantalum liners. It is noted that these optimum standoff distances are based on the penetration depth, not the radius of penetration.

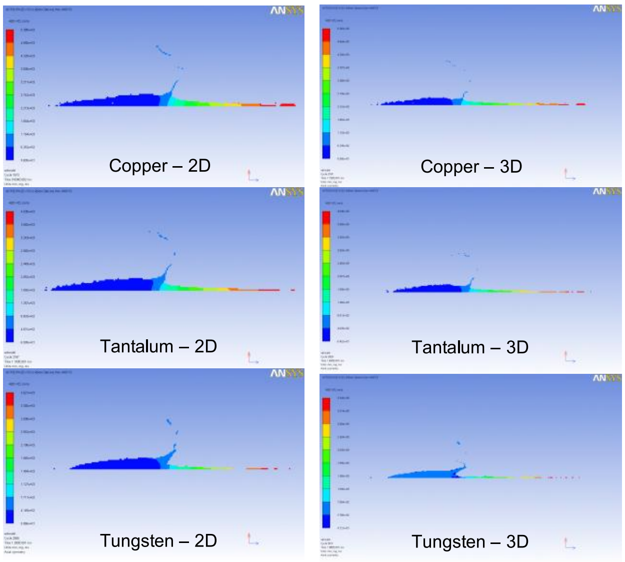

Fig. 4 Simulated jets before reaching the target at standoff distances 2D and 3D

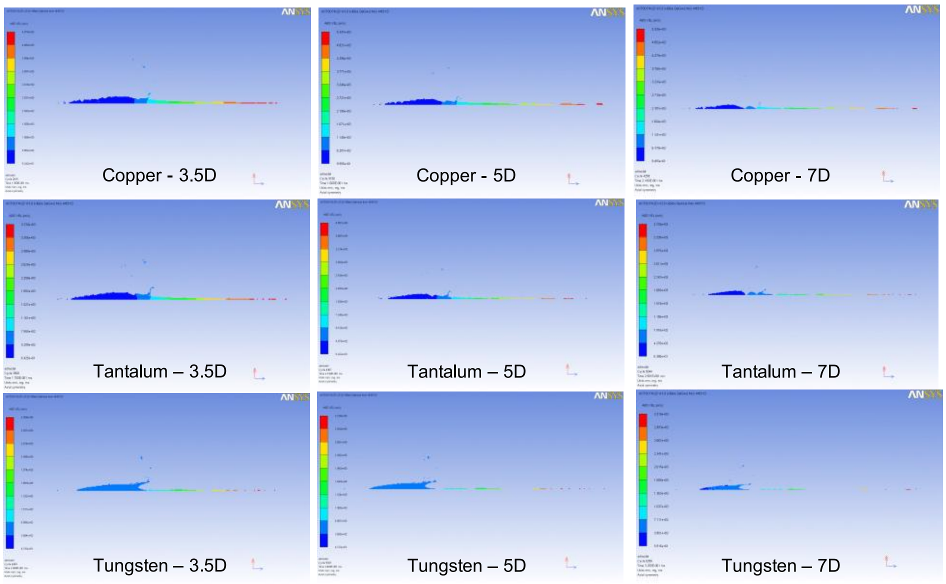

Fig. 5 Simulated jets before reaching the target at standoff distances 3.5D, 5D and 7D

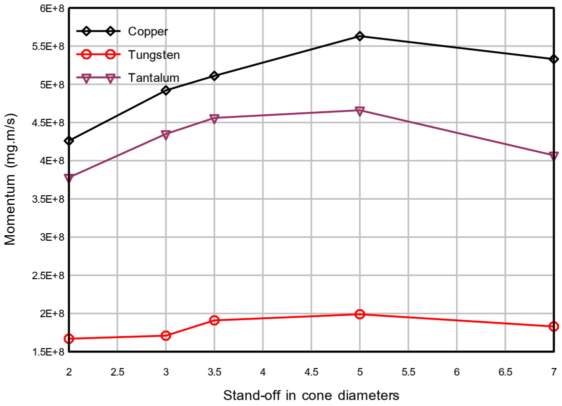

Fig. 6 Momentum of jet from different liner materials

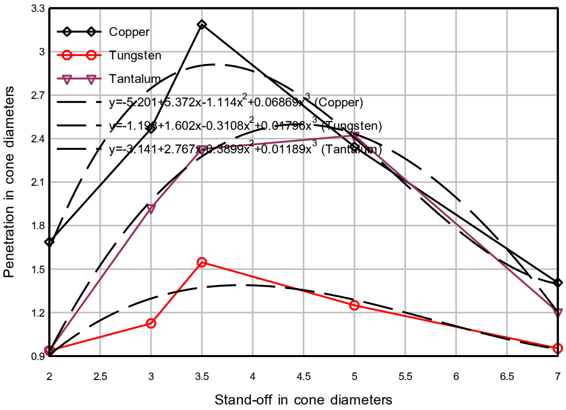

Fig. 7 Standoff distance and penetration curves for different liner materials

Table 4 Optimum standoff distances and their corresponding penetration depths

Liner material	Optimum standoff distance in cone diameter	Penetration in cone diameter
Copper	3.63	2.91
Tungsten	3.89	1.39
Tantalum	4.46	2.50

4. Conclusions

This research paper presents a series of numerical studies of shaped charge warheads detonated at various standoff distances. Numerical simulation was employed to investigate different liner materials, which are copper, tantalum and tungsten, in order to investigate their penetration capability. The results reveal that the copper jet generally penetrates at the greatest depth compared to those obtained from tantalum and tungsten jets.

In addition, the shaped charge warheads using copper and tungsten liners should be detonated at 3.63D and 3.89D standoff distance, respectively, in order to achieve maximum penetration. The optimum standoff distance for shaped charge warhead using a tantalum liner is found to be 4.46D. It is noted that the largest radius of penetration may not be obtained at these optimum standoff distances.

5. References

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