

Effects of the liner materials on penetration capability of explosively formed projectiles

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ABSTRACT

Numerical simulations are carried out to study the effects of the liner material (Al, Cu, Mo, W, Ta) on the shape, mass, velocity, kinetic energy, length-to-diameter ratio, penetration depth and hole-diameter of MCT-83 mine (explosively formed projectile). The results of these parameters present the potential capability of each liner material used to fabricate explosively formed projectiles. Cu has get the maximum penetration depth value while Mo has the largest hole-diameter. The research results help to choose the material of liner suitable for each type of EFP warhead and for each different purposes.

Keywords: EFP; MCT-83; Material; Penetration of EFP.

1. INTRODUCTION

Explosively formed projectiles (EFP) is a kind of shaped charge structure which has high penetration capability and large standoff. EFP has velocity about $1500 \div 2500$ m/s, target destruction standoff of up to 1000 charge-caliber and penetration capability to $0,3 \div 1$ charge-caliber [1, 4]. EFP is used to destroy tanks, armored vehicles in positions with thin thickness such as the side or roof of tank at distance of up to 50 m and possibly further [3].

These days, EFP warheads are present in weapon systems such as: CBU-97, CBU-105, BLU-108 Air Force Cassette Bombs; Anti-tank mines M303 of the US, TM-72, TM-83, TM-89 of Russia; SMArt-155, etc. There are no EFP weapons in Viet Nam.

The material of liner is one of the important factors affecting the penetration capability. It must have high density, high ductility, high strength, no toxicity and high enough melting temperature to avoid melting in the liner due to adiabatic heating under explosive loading [8]. Usually, it is made of metal because it is cheap and easy to fabricate. The most common liner materials for EFP are copper, mild steel, tantalum and tantalum-tungsten alloys.

There are many studies about EFP, experimental and numerical study the formation, flight and penetration performance of EFP [10-16]. However, effects of liner materials on penetration capability have not been studied. There are some works about liner material such as: the effects of the liner material (MS, Cu, Fe, Al, Ta) on the shape, velocity, traveled distance, pressure, internal energy, temperature, divergence or stability, density, compression, and length-to-diameter ratio [8], the influence of liner material on the dynamic response of the steel target [13].

In this paper, we study the effects of the liner materials such as: Copper (Cu), Tantalum (Ta), Aluminum (Al), Molybdenum (Mo) and Tungsten (W) to evaluate the effects as well as the degree of effect of these materials on the penetration capability. In addition, evaluating the parameters of the rod such as: velocity, mass, kinetic energy, shape, length-to-diameter ratio. It is the basis to be able to choose suitable materials for different purposes.

2. THEORETICAL FOUNDATIONS AND CALCULATION METHODS

Nowdays, the development of numerical simulation, it is possible to simulate complex explosion physics problems. The combination of simulation and experiment allows us to deeply

understand the process of forming and penetrating of EFP, reducing a lot of effort and cost in the process study. According to [2], the paper has studied and built a simulation model of the process of forming and penetrating the steel plate at a distance of 5 m of the MCT-83 anti-tank mine using Ansys Autodyn 2D software. The simulation results are 4,45% different from the experimental results. Therefore, it is possible to apply numerical simulation method to study the effects of liner materials on the steel penetration capability of MCT-83 anti-tank mine or the EFP warheads.

Geometric model of the MCT-83 mine is shown in figure 1. The MCT-83 mine has case made of 45# steel, TT-40 (Comp B) explosive, a liner is made of Grade M1 copper and material of steel plate is 40X steel [3].

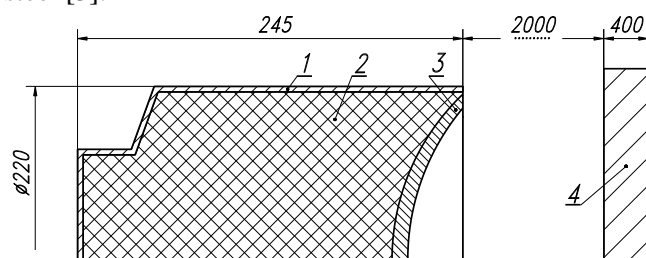


Figure 1. Geometric model of the MCT-83 mine (in mm).

1. Case; 2. Explosive; 3. Liner; 4. Steel plate.

The behavior of the used explosives, has been described by the Jones -Wilkins - Lee (JWL) equation of state, together with the programmed burn model. The JWL equation has the form [4, 5].

$$p = A \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

where p is the pressure; V and E are represented as $V = \frac{\rho_0}{\rho}$, $E = \rho_0 \cdot e$, ρ_0 is the current density, ρ is the reference density, e is the specific internal energy; A , B , R_1 , R_2 , and ω are the material properties of the chemical high explosive [7]. The initial values of these constants used in the simulation are $\omega = 0,34$; $A = 5,2423 \cdot 10^8$ kPa; $B = 7,678 \cdot 10^6$ kPa; $R_1 = 4,2$; $R_2 = 1,1$; $\rho = 1,717$ g/cm³; $D = 7980$ m/s; $E_0 = 8,5 \cdot 10^9$ J/m³.

Mathematical model to describe the material properties of the case, liner and steel plate is the equation of state and the strength model. Because these materials are subjected to rapidly varying impulse loads (explosive and impact loads), according to [7-10] the equation of state usually uses the Shock equation of state, the model of strength usually uses Johnson-Cook or Steinberg-Guinan model.

The commonly Shock equation of state is Rankine- Hugoniot describing the jump conditions, determining the relationship between any two pairs of variables in the variables ρ (density), p (pressure), e (energy), u_p (particle velocity) and U (shock velocity). In most solid materials and some liquids, U and u_p are related [7]:

$$U = C_0 + S_1 \cdot u_p + S_2 \cdot u_p^2 \quad (2)$$

where C_0 , S_1 and S_2 are constants.

The Johnson-Cook model is applied to the case and steel plate materials. The yield stress depends on the degree of strain, strain rate and temperature [7].

$$\sigma_c^d = (A + B \varepsilon_p^n) (1 + C \ln \varepsilon_p^*) \left(1 - \left(\frac{T - T_0}{T_{nc} - T_0} \right)^m \right) \quad (3)$$

The expression in the first brackets gives the stress as a function of strain; the expressions in

the second and third brackets represent the effects of the strain rate and temperature, respectively, ε_p is the effective plastic strain, $\dot{\varepsilon}_p^*$ is normalized effective plastic strain rate, A, B, n, C, and m are the material constants, T_0 and T_{nc} are the reference and melting temperatures of the material.

Case material properties are described by equation (3) with the following constants [10]: $A = 3,5 \cdot 10^5$ kPa; $B = 5,531 \cdot 10^5$ kPa; $n = 0,234$; $m = 1$; $C = 0,0134$; $T_{nc} = 1733$ K. Beside, steel plate material properties are $A = 4,55 \cdot 10^5$ kPa; $B = 5,1 \cdot 10^5$ kPa; $n = 0,26$; $m = 1,03$; $C = 0,014$; $T_{nc} = 1793$ K.

The Steinberg-Guinan model is applied to liner materials. When the strain rate is greater than 10^5 s^{-1} , the strain rate is not significantly affected compared to other factors. The shear modulus increases with increasing pressure and decreases with increasing temperature. The shear modulus and strength limit are a function of the effective plastic strain, pressure, and internal energy (temperature).

The shear modulus and strength limit are determined as follows [7]:

$$G = G_0 \left\{ 1 + \left(\frac{G'_p}{G_0} \right) \frac{p}{\eta^{1/3}} + \left(\frac{G'_T}{G_0} \right) (T - 300) \right\} \quad (4)$$

$$\sigma_c^d = \sigma_c^0 \left\{ 1 + \left(\frac{(\sigma_c^d)'_p}{\sigma_c^0} \right) \frac{p}{\eta^{1/3}} + \left(\frac{G'_T}{G_0} \right) (T - 300) \right\} (1 + \beta \varepsilon)^n \quad (5)$$

Subject to $\sigma_c^0 (1 + \beta \varepsilon)^n \leq \sigma_{c_{max}}^d$.

Where: T is Temperature (K); p is pressure; ε is effective plastic strain; G, σ_c^d are shear modulus and yield stress; G_0 , σ_c^0 are shear modulus and yield stress at the reference state ($T = 300$, $p = 0$, $\varepsilon = 0$); β , n are the material constants; η is compression v_0 / v ; G'_p , G'_T , $(\sigma_c^d)'$ are derivatives of G and σ_c^d . Constants of liner materials are shown in table 2.

The system of mathematical equations describing the process of forming and penetrating into the steel plate, the boundary conditions, the initial conditions, the stopping conditions are taken according to [2].

The process of forming and penetrating the steel plate is divided into three stages, including: the forming of rod stage, the rod moving in the air and the rod hitting the steel plate. Therefore, the simulation model is also divided into three corresponding stages.

The formation and movement of rod in the air uses Euler solver, and the penetration process uses Lagrange solver. Case, liner, explosive are filled with multi-material Euler mesh [8-10], using Lagrange mesh for steel plate and rod to simulate the penetration process.

The simulation model of the process of forming, moving in the air and penetrating the steel plate, which is built on Ansys autodyn 2D software as shown in figures 2, 3, 4.

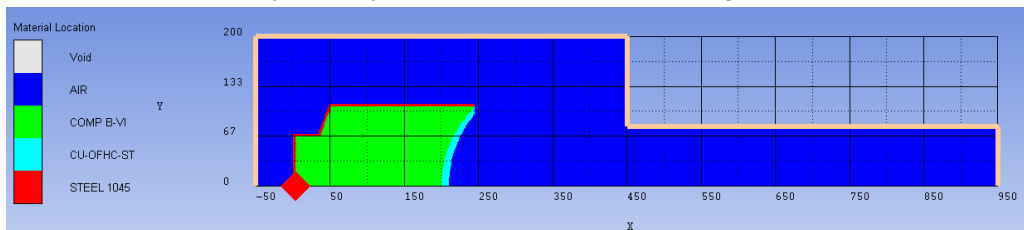


Figure 2. Simulation model of forming process (in mm).

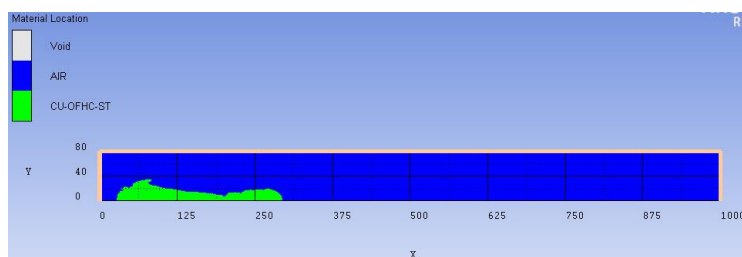


Figure 3. Simulation model of moving in the air of rod (in mm).

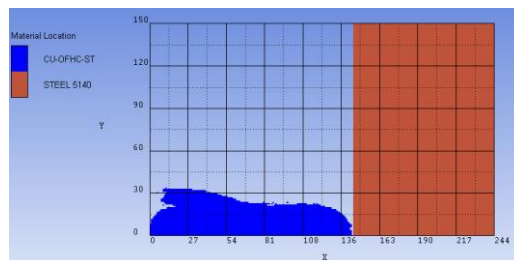


Figure 4. Simulation model of penetrating the steel plate (in mm).

3. RESULTS AND DISCUSSION

To investigate the effects of liner materials on the steel penetration capability, the simulation problem was changed with different materials: Aluminum, copper, molybdenum, tantalum, tungsten. The values of material parameters are presented in tables 1 and 2, specifically as follows [7]:

Table 1. Values of the parameters of the equation of state of the materials.

No.	Material	ρ , g/cm ³	Γ	C_1 , m/s	S_1	T_0 , K	C_p , J/kgK
1	Aluminum	2,707	1,97	$5,386.10^3$	1,339	300	884
2	Copper	8,93	2,02	$3,94.10^3$	1,489	300	383
3	Molybdenum	10,2	1,59	$5,143.10^3$	1,255	300	243
4	Tantalum	16,69	1,67	$3,41.10^3$	1,2	300	135
5	Tungsten	19,3	1,67	$4,03.10^3$	1,237	300	129

Table 2. Values of the parameters of the Steinberg- Guinan model.

No.	Material	G, kPa	σ_c^0 , kPa	$\sigma_{c\max}^0$, kPa	β	η	G_p'	G_T'	$(\sigma_c^d)'_p$	T_{nc} , K
1	Aluminum	$2,71.10^7$	$4,0.10^4$	$4,8.10^5$	400	0,27	1,767	$-1,699.10^4$	$2,608.10^{-3}$	1220
2	Copper	$4,77.10^7$	$9,7.10^4$	$6,4.10^5$	36	0,45	1,35	$-1,798.10^4$	$3,396.10^{-3}$	1790
3	Molybdenum	$1,25.10^8$	$1,6.10^6$	$2,8.10^6$	10	0,1	1,425	$-1,9.10^4$	$1,824.10^{-2}$	3660
4	Tantalum	$6,90.10^7$	$7,7.10^5$	$1,1.10^6$	10	0,1	1,0	$-8,97.10^3$	$1,117.10^{-2}$	4340
5	Tungsten	$1,60.10^8$	$2,2.10^6$	$4,0.10^6$	7,7	0,13	1,501	$-2,208.10^4$	$2,064.10^{-4}$	4520

Calculation results of velocity, mass, shape and penetration depth are presented in table 3. Where ω_{TN} is the explosive mass, ω_D is the liner mass, E is kinetic energy, and V_c is the impact velocity at the distance 2 m, b is penetration depth, D_x is hole-diameter.

Among the investigated materials, aluminum has the lowest density, melting temperature, and dynamic yield stress. Tungsten has the highest density, melting point, and dynamic yield stress. Tantalum has density, melting temperature higher than copper and molybdenum, but has lower dynamic yield stress than molybdenum. The ratio of the density of copper, molybdenum, tantalum, tungsten to aluminum is: 3,29; 3,76; 6,16; 7,13.

The mass ratio between explosive and liner for aluminum is the largest (15,38). Copper and molybdenum are 4,05 and 4,63 and tantalum and tungsten are 2,48 and 2,15.

Table 3. Calculation results of velocity, mass, shape and penetration depth with different materials.

No.	Material	ω_{TN} , kg	ω_D , kg	ω_{TN}/ω_D	Vc, m/s	Mass of rod, kg	E, MJ	l/d	b, mm	D _x , mm
1	Aluminum	12	0,78	15,38	3730	0,78	5,43	3,23 (226/70)	90	80
2	Copper	12	2,59	4,63	1952	2,47	4,71	2,17 (143/66)	143	106
3	Molybdenum	12	2,96	4,05	1768	2,96	4,63	0,32 (46/144)	101	184
4	Tantalum	12	4,84	2,48	1251	3,98	3,11	0,77 (71/92)	103	130
5	Tungsten	12	5,59	2,15	1102	5,59	3,39	0,30 (51/170)	45	168

The effects of materials on impact velocity and kinetic energy

According to the calculation results, the survey materials are divided into 3 velocity groups. Aluminum has the highest velocity (3730 m/s) 3,38 times higher than tungsten (1102 m/s). Copper and molybdenum have the same group of velocities as 1952 m/s and 1768 m/s. Tantalum and tungsten are in the lowest velocity group. Velocity of aluminum exceeds the normal velocity range of EFP, while tantalum and tungsten are lower.

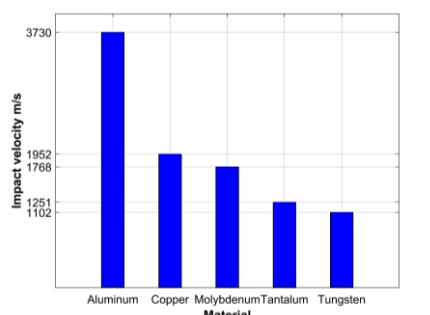


Figure 5. Graph of the effects of materials on impact velocity.

The velocity of rod is inversely proportional to the density of the material, the melting temperature and directly proportional to the ratio ω_{TN}/ω_D . The law of change of velocity is not equivalent to the change of dynamic yield stress. Tantalum has a dynamic yield stress lower than molybdenum and higher than copper, but the velocity of rod is smaller than that of copper and molybdenum.

Although Aluminum has small mass but high velocity, it has the largest kinetic energy (5,43 MJ). Because of the loss of mass during formation and low velocity, tantalum has the smallest kinetic energy (3,11 MJ). Copper and molybdenum have almost the same kinetic energy and are larger than that of tantalum and tungsten at 4,71 MJ and 4,63 MJ.

The effects of materials on size, shape of rod

l/d ratio of aluminum is the largest (3,23), molybdenum and tungsten are the smallest. Although copper and molybdenum have similar densities and velocities, copper's l/d ratio is much larger than molybdenum's (6,78 times). Because the melting temperature and dynamic yield stress of molybdenum are higher than copper. Based on size of rod, we can predict that molybdenum and Tungsten will have the largest hole-diameter.

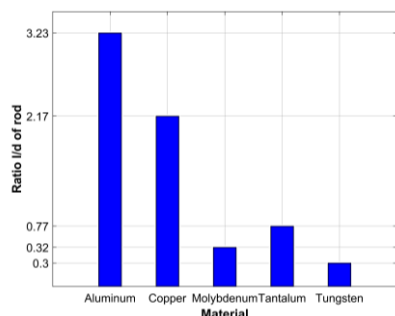


Figure 6. Graph of the effects of materials on ratio l/d of rod.

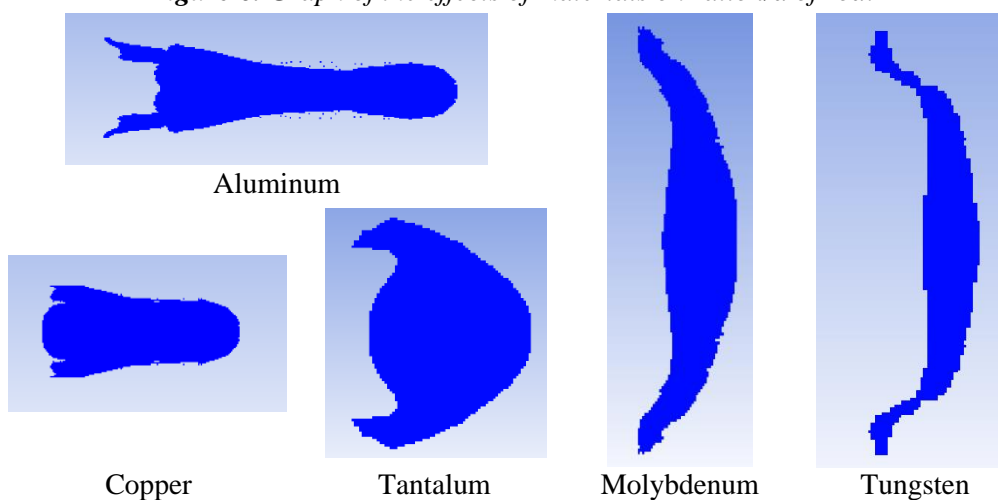


Figure 7. Shape of rods with different materials.

The effects of materials on penetration depth and hole-diameter

Simulation results show that copper has the maximum penetration depth (143 mm), tungsten has the minimum penetration depth (45 mm). Aluminum has the minimum hole-diameter (80 mm), molybdenum has the maximum hole-diameter (184 mm).

Although the velocity and kinetic energy of aluminum is the highest, it has not get the maximum penetration depth. The penetration result of aluminum demonstrate that kinetic energy has little influence on the penetration capability.

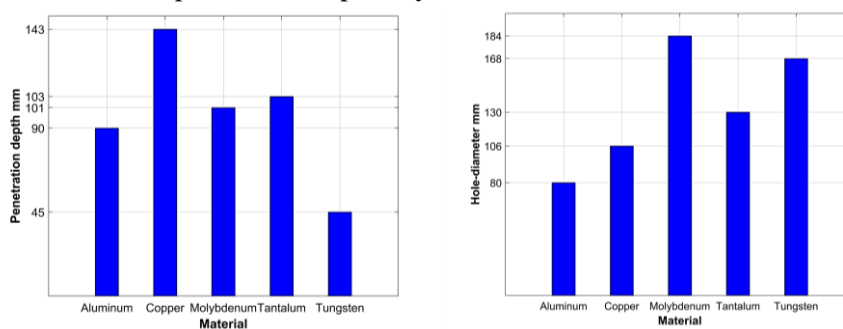


Figure 8. Graph of the effects of material on penetration depth and hole-diameter.

Tantalum has low velocity, but the suitable diameter of rod and the dynamic yield stress is high, so the capability to penetrate steel is high. Tungsten has the same velocity as tantalum and the dynamic yield stress is higher. However the large diameter of the rod leads to a large resistance which makes low penetration capability.

4. CONCLUSIONS

Aluminum is the liner material that shows an immediate response to the impacted shock wave, resulting in the highest velocity, kinetic energy, and l/d ratio due to its softness, low initial density, low melting temperature, and interatomic structure. The rod of tungsten and molybdenum have a large diameter, which enables them to produce a wider through hole in the target.

Keeping the other parameters in mind for this particular design of MCT-83 mine, EFPs made of copper are preferable material with deeper penetration ability. It possesses most optimal parameters of rod such as velocity, l/d ratio. Therefore, its penetration ability gets the maximum value.

For armored vehicles with thin thickness, it is recommended to use liner made of molybdenum or tungsten to create large hole -diameter, in order to increase the possibility of damage behind the steel plate.

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TÓM TẮT

Ảnh hưởng vật liệu đĩa tạo hình đến khả năng xuyên thép của đạn nổ tạo hình

Mô phỏng số được thực hiện để nghiên cứu ảnh hưởng của vật liệu đĩa tạo hình (Al, Cu, Mo, W, Ta) đến hình dạng, khối lượng, vận tốc, động năng, tỷ số chiều dài- đường kính, chiều sâu xuyên và đường kính lỗ xuyên của đạn nổ tạo hình. Kết quả của các tham số này cho thấy khả năng của từng vật liệu đĩa tạo hình được sử dụng để chế tạo đạn nổ tạo hình. Đồng có giá trị chiều sâu xuyên lớn nhất trong khi molyden có đường kính lỗ xuyên lớn nhất. Kết quả nghiên cứu giúp cho việc lựa chọn vật liệu của đĩa tạo hình phù hợp cho từng loại đạn và từng mục đích khác nhau.

Từ khóa: EFP; MCT-83; Vật liệu; Chiều sâu xuyên.