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NUMERICAL MODELING OF EXPLOSIVELY FORMED PROJECTILES FORMATION

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Abstract: *Within this study, the process of forming explosively formed projectiles is analyzed. This type of warhead is used for military purposes due to its excellent impact performance. The projectile is shaped like a metal disc which, during the action of the explosive, forms into a high-speed projectile. Such formed projectiles act on the target. The performance of the projectile is influenced by a large number of parameters, such as structural characteristics and material properties. Using a numerical program on the EFP model, various parameters influencing the final shape of the projectile and thus its performance on the target can be analyzed. The parameters considered within this study are the type of explosive filling and the thickness of the copper disc. The analyzed disc thickness was 1-4% of the explosive filling diameter. It was observed that reducing the thickness of the projectile results in higher values of projectile stable velocity. Specifically, reducing the initial thickness of the projectile can replace the use of more explosive explosives, thereby reducing the overall mass of the construction.*

Keywords: *Explosively formed projectile, EFP, High-speed projectile, Numerical modeling*

1. INTRODUCTION

The explosively formed projectile (EFP) belongs to a group of warheads where explosive filling is used to accelerate the penetrator (formed disc) to high speeds. This type of warhead possesses a penetrator with a specific shape that is maintained until contact with the target [1].

Also, it belongs to the group of directed energy warheads, which focus explosive energy using the shape of a disc. EFP warheads can produce penetrators at speeds of 2-3 km/h [1]. In such cases, these warheads utilize most of casing for forming the penetrator.

The penetrator for the EFP is generally a bow-shaped metal part, called a self-forging fragment or ballistic disc. Warhead with shaped charge generally use a narrow cone-like geometry [2]. There is no clear line between shaped charge and EFP. A wide angle and a thick layer of shaped charge can form an EFP penetrator [1].

Most commonly, the shaped charge consists of an initial array with a detonator for forming a suitable circular detonation wave in the explosive filling, which, upon detonation, transforms the disc at the opposite end of the detonator.

After the explosive is initiated, a spherical detonation wave propagates forward from the initiation point. This high-pressure shock wave propagates at the detonation velocity of typical explosives (>8 km/s) and with a pressure equal to the Chapman-Jouget (CJ) pressure (P_{cj}>0.25 Mbar) [1]. When the detonation wave reaches the material of the disc, it accelerates along the axis of symmetry and collapses towards the symmetry axis. The collapse of the disc material onto the central line forces the disc to move at high speed.

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Due to this high speed, the penetrator can be transported to the target. Upon penetration of the penetrator into the target, the first element of the penetrator creates a hole. The second element impacts the target at the bottom of where the first element hit. Penetration continues as long as the penetrator has kinetic energy.

The entire process from explosive detonation to complete penetration occurs in less than half a millisecond, for short target distances. Due to the extremely high pressures, short duration, and harsh environment present in the penetrator/target interaction region, this is an exceptionally complex phenomenon.

The first publications related to this topic, i.e., to warheads similar to EFP, appeared in 1935 and 1936. However, research on this topic increased in the 1970s [3]. A large number of authors have presented various dependencies on the geometry of these projectiles, which can positively or negatively affect projectile performance. Among the significant parameters is the thickness of the casing, or the variability of its thickness, which is one of the more important factors, as well as the distance from the detonator center. Additionally, an important parameter is the ratio of the disc thickness to its diameter, which should be in the range of 4-7 %. [3] One of the most significant parameters is the ratio of width to height, or the ratio of length to diameter of the explosive before detonation. [4] A ratio of width to height can increase kinetic energy to a maximum of 1.5. [3]

The shape of the disc is an important parameter. The geometric shape can be hemispherical, hyperbolic, etc. In addition, the diameter and thickness of the disc are also crucial. According to data, the thickness of the disc occupies 1-4 % of the diameter of the explosive filling, while some projectiles can have a thickness of up to 8 % of the filling diameter. [5] The thickness of the disc can be variable, but care should be taken to ensure that the thickness does not change suddenly, as this can negatively impact disc performance [5]. Thinner discs may have a better effect than thicker ones and may achieve higher speeds [5]. It's essential to ensure that the disc thickness does not decrease infinitely, as this can cause the formed disc to rupture. The material of the disc plays a crucial role. It's necessary for the material to have a high melting point, high density, a closed crystal structure, good tensile characteristics, and to be free of impurities [5]. Additionally, the disc material should be easily deformable. The material of the disc is primarily copper because copper achieves maximum penetrations [6].

The height of the filling, i.e., the distance between the top of the explosive filling and the initiation point, represents an important factor. It's necessary for this distance to be sufficient to ensure that the detonation wave becomes flatter when it reaches the disc [5]. If the wave reaching the disc has a spherical shape with a smaller radius, then the filling height is inadequate and does not uniformly transmit to the disc. Generally, the velocity, energy, and penetration depth of EFP increase with the increase in distance. However, the filling height should not be increased infinitely. The ideal filling height is from 1 to 1.5 times the filling diameter, without a deflector [5].

If a wave shaper is present in the construction of the EFP, its shape affects the shape of the detonation wave. The wave shaper is intended to redirect the detonation wave to more desirable, i.e., to reduce the angle of attack (the angle between the detonation wave and the disc), thereby more evenly transferring the wave energy to the disc. During initiation, the detonation wave "bypasses" the wave shaper, and then the detonation waves collide on the axis of the explosive filling. If the angle of incident is smaller than the critical Mach reflection angle, then regular reflection occurs, and the pressure at the collision point is 2.4 times greater than the CJ pressure [7, 8]. However, if the incident angle exceeds the critical angle, then Mach reflection occurs, where the pressure behind the Mach wave drops from four times the CJ pressure to normal pressure [7, 8]. It's essential to consider the shape of the wave shaper and its dimensions.

The explosive filling can be incorporated into the casing of the EFP through either casting or pressing processes. Regardless of the method, it's essential for the density and granulation of the explosive to be uniform to achieve the intended warhead effect.

2. NUMERIC MODEL

2.1. Material properties

The material of the disc is copper, which is described using the Johnson-Cook (JC) equation:

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon})\left(1 - \left|\frac{T - T_r}{T_m - T_r}\right|^m\right) \quad (1)$$

Where are A, B, C, n, and m - material parameters; ε - the plastic strain; $\dot{\varepsilon}$ - the strain rate; T_m - the reference temperature; T_r - the melting temperature of copper [3, 9]. The specified parameters for copper are shown in Table 1. The reason for using the Johnson-Cook constitutive method is that it provides better results for copper projectiles. This model accounts for thermal softening. Copper has a low melting temperature and a high thermal softening component [10]. The material of the casing is aluminum. Data for aluminum are provided in Table 2.

The explosive fillings are octogen (HMX), phlegmatized octogen (HMX-INERT), and explosive LX-10-1. The equation of state for the explosive is the Jones-Wilkins-Lee (JWL) equation of state:

$$P = A\left|1 - \frac{\omega}{R_1 V}\right| e^{-R_1 V} + B\left|1 - \frac{\omega}{R_2 V}\right| e^{-R_2 V} + \frac{\omega E_0}{V} \qquad (2)$$

Where is P - the shock wave pressure; V - the volume ratio between the detonation products and the initial explosive; A, B, R_1, R_2, and ω - material parameters; E_0 - the specific internal energy of the explosive [3, 9]. The data are provided in Table 3.

Table 1. Characteristics of copper

COPPER	
Density [kg/m^3]	8960
Specific Heat [J/kgK]	383
Johnson Cook Strength	
Initial Yield Stress [Pa]	9E+07
Hardening Constant [Pa]	2.92E+08
Hardening Exponent	0.31
Strain Rate Constant	0,025
Thermal Softening Exponent	1.09
Melting Temperature [°C]	1082.9
Reference Strain Rate [1/sec]	1
Bulk Modulus [Pa]	1.29E+011
Shear Modulus [Pa]	4.6E+11

Table 2. Characteristics of aluminum

ALUMINUM (AL 6061-T6)	
Density [kg/m^3]	2703
Specific Heat [J/kgK]	885
Steinberg Guinan Strength	
Initial Yield Stress [Pa]	2.90E+08
Maximum Yield Stress	6.8E+08
Hardening Constant	125
Hardening Exponent	0.1
Strain Rate Constant	0.025
Melting Temperature [°C]	946.85
Shear Modulus [Pa]	2.76E+10
Shock EOS Linear	
Gruneisen Coefficient	1.97
Parameter C1 [m/s]	5240
Parameter S1	1.4
Parameter Quadratic S2 [s/m]	0

Table 3. Characteristics of selected explosives

Characteristics	HMX	HMX-INERT	LX-10-1
Density [kg/m^3]	1891	1783	1865
Explosive JWL			
Parameter A [Pa]	7.7828E+11	9.4334E+11	8.807E+11
Parameter B [Pa]	7.0714E+09	8.8053E+09	1.84E+10
Parameter R1	4.2	4.7	4.62
Parameter R2	1	0.9	1.32
Parameter W	0.3	0.35	0.38
Detonation velocity [m/s]	9110	8730	8820
Energy per unit mass [J/kg]	5.55E+06	5.72E+06	5.58E+06
Pressure [Pa]	4.20E+10	3.35E+10	3.75E+10

The detonator material is explosive C4, the data for which are provided in Table 4. The wave shaper material is polyethylene, and its data are given in Table 5.

Table 4. Characteristics of C4 explosive

C4	
Density [kg/m^3]	1601
Explosive JWL	
Parameter A [Pa]	6.0977E+11
Parameter B [Pa]	1.30E+10
Parameter R1	4.5
Parameter R2	1,4
Parameter W	0.25
C-J Detonation Velocity [m/s]	8193

	C-J Energy per unit mass [J/kg]	5.62E+06
	C-J Pressure [Pa]	2.80E+10

Table 5. Characteristics polyethylene

POLYETHYLENE		
Density [kg/m^3]		915
Shock EOS Linear		
	Gruneisen Coefficient	1.64
	Parameter C1 [m/s]	2901
	Parameter S1	1.481
	Parameter Quadratic S2 [s/m]	0

2.2. Calculation model

The EFP model is shown in Figure 1. The Eulerian model describes the casing, detonator, wave shaper, and explosive filling. Meanwhile, the disc is described using the Lagrangian model. The Lagrangian model is used for "structural" elements, where the numerical mesh moves and deforms with the material motion. The Eulerian model is used for large movements and explosives, where the numerical mesh is fixed, and the fluid flows through the mesh. [1] The mesh size is 0.5 mm. Since the model is axisymmetric, only a quarter of the model is considered. The model is observed in 2D.

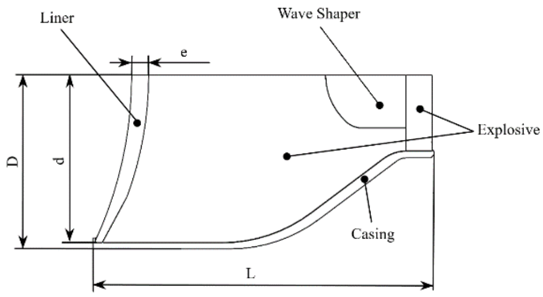

Figure 1. EFP, where are: D – casing diameter; d – disc diameter; e – disc thickness; L – casing length

3. RESULTS

The previously shown EFP model with different explosive fillings was analyzed in the corresponding numerical program. Additionally, the disc thicknesses were varied, starting from 5.3 mm and gradually reduced to 4.9 mm. Figure 2 illustrates the disc formation over time for an example of EFP with phlegmatized HMX explosive filling and a disc thickness of 5.3 mm.

The disc formation is a complex dynamic process primarily resulting from the interaction between various components of the warhead. The stability of flight velocity is achieved at approximately t = 400 µs [3]. In this case, it was observed that the stability of flight velocity occurs at around 300 µs.

It is noticeable that the EFP with LX-10-1 explosive attains the highest disc velocity, slightly higher compared to the EFP with octogen. Conversely, the disc with phlegmatized octogen exhibits the lowest velocity. It is concluded that the EFP with LX-10-1 explosive causes the most significant elongation of the formed disc. Conversely, the EFP with phlegmatized octogen exhibits the shortest formed disc. It was observed that during the formation of the disc with stronger explosives (in this case, LX-10-1 and HMX), narrowing of the projectile's rear part occurs, which does not happen with the action of weaker explosives, such as phlegmatized octogen.

Based on Figure 3, it can be observed that reducing the disc thickness leads to an increase in its velocity during formation. Decreasing the disc thickness with weaker explosives can replace the use of stronger explosives. However, the disc thickness should not be reduced infinitely. Excessive reduction in disc thickness leads to the collapse of the disc structure during formation and results in irregular disc formation, which can cause projectile fragmentation and consequently irregular action on the target. The process of reducing disc thickness also contributes to reducing the overall mass of the construction.

The ballistic performance of the obtained projectile is evaluated based on criteria related to its kinetic energy. Ballistic parameters such as geometry, detonation type (number and position of detonators), and materials influence the stable flight velocity of the EFP and consequently its penetration stability (i.e., ballistic performance) [3].

Table 6 provides stable velocities, kinetic energy, and specific energy of the formed projectile for different disc thickness values. Based on the presented table, it is observed that the model of EFP with LX-10-1 explosive has the highest kinetic energy, which is expectedly proportional to the disc mass. However, the variant with the lowest mass also has significantly high kinetic energy due to the high disc velocity. The same applies to the specific energy of the formed projectile, which is significant for projectile penetration through obstacles.

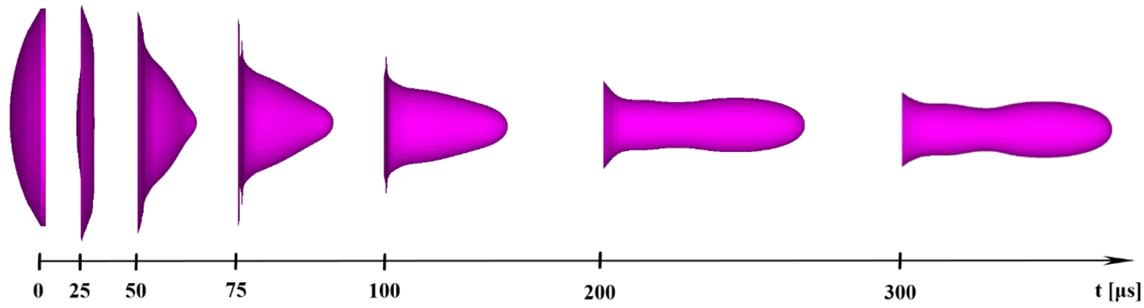

Figure 2. Display of disc formation over time, with an EFP containing HMX-INERT explosive fill and a disc thickness of 5.3 mm

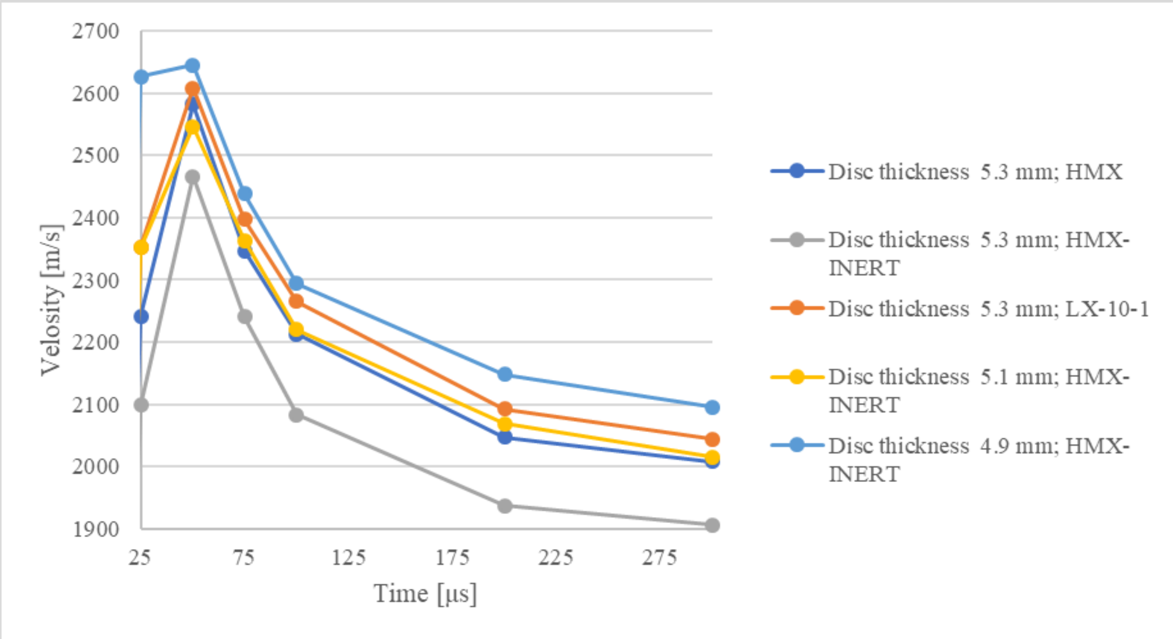

Figure 3. Diagram of the velocity change at the apex during disk formation

Table 6. Stable velocity and kinetic energy for different values of disk thickness

	Disc thickness 5.3 mm			**Disc thickness 5.1 mm**	**Disc thickness 4,9.mm**
	LX-10-1	**HMX**	**HMX-INERT**	**HMX-INERT**	**HMX-INERT**
Disc mass [g]	320	320	320	296.8	282.5
Stable velocity [m/s]	2044	2008	1906.3	2016	2095.6
Kinetic energy [kJ]	668469.8	645066	581436.7	603075.8	620304.9
Formed penetrator diameter [mm]	21.2	21.7	25.2	22	20.8
Specific energy [kJ/mm^2]	473.4	434.4	291.4	396.6	456.4

4. CONCLUSION

A large number of parameters affect the final shape of the penetrator. It's necessary to harmonize all parameters to achieve the desired effect on the target. Analyzing the presented EFP construction with different explosive fillings led to certain conclusions.

Firstly, when using explosives that are stronger according to their characteristics, penetrators of higher speeds are formed compared to the values of speeds when using weaker explosives. However, by reducing the thickness of the disk and using weaker explosives, higher values of stable speeds are obtained. These values are higher compared to the values of stable speeds when using stronger explosives.

Kinetic energy, as an indicator of ballistic performance, is greater in penetrators with stronger explosives and greater penetrator thickness, proportionally to the greater mass of the penetrator. However, using stronger explosives can lead to thinning of the rear part of the penetrator. This can cause the penetrator to break during flight and result in less kinetic energy reaching the target. Therefore, it is recommended to use weaker explosives with a smaller initial disk thickness to obtain a compact penetrator with high kinetic energy at the target. It is necessary to confirm the obtained data with experiments to validate numerical simulations, which represents the next step in this comprehensive topic.

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