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Design of Shaped Charges With Optimum Armored Penetration Efficiency

Kerem Can Albayrak[#,*], Murat Üçüncü[#] and Faruk Elaldi[$]

[#]Department of Defense Technologies and Systems, Baskent University, Ankara
[$]Department of Mechanical Engineering Baskent University, Ankara
[*]E-mail: keremcalbayrak@gmail.com

ABSTRACT

In this article, we investigated several alternatives about how to increase the penetration efficiency by only changing the shaped charge liner geometries without changing the other warhead dimensions. In this context, 3 different orthographic designs were realised in 2 dimensions in conical, trumpet and ellipsoid geometries like the standard warhead dimensions in the literature. Simulations were carried out to specify the parameters that allow the determination of the most appropriate penetration efficiency with the selected liner geometries. After the type of the explosive and liner material together with liner thickness were determined, simulations of 3 different liner geometries were tested through AUTODYN to determine the jet formations and armor penetration efficiency values and the obtained values were compared with each other. As a result, it is understood that the highest penetration depth is achieved with the "Trumpet geometry" when the desensitized HMX explosive material, 1.5 mm liner thickness, and stand-off distance with a length of 1.5 times of Charge Diameter (CD) were used. Considering these results, it is appropriate to design a Shaped Charge Liner (SCL) with Trumpet geometry, and if a large penetration hole is desired in the armor, it is appropriate to design a SCL with Ellipsoid geometry.

Keywords: Warhead; Shaped charge; Jet formation; Armor penetration; Explosive

NOMENCLATURE

CD	: Charge diameter
C-J	: Chapman-Jouguet
HMX	: High melting explosive
RDX	: Royal demolition explosive
SCL	: Shaped charge liner
P	: Density
σ_y	: Yield strength

1. INTRODUCTION

The manufacturing process of hollow shaped charge explosives ensures that the detonation energy is directed in a very narrow direction. These explosives are used in warheads as well as to activate missiles, pierce armor, cut or shape metals. A hollow (cavity) volume that can adapt to any geometrical shape such as a hemisphere, cone, or similar can focus the energy generated by the explosion of the gases formed in these geometries to a point[1].

The performance of the shape charge depends on the cone apex angle, cone geometry such as, cone, cone with a rounded top, hemisphere, ellipsoid, trumpet, type of the liner material (copper, aluminum etc.), explosive (TNT, RDX and Comp-B) and the stand of distance (Fig.1). In addition to these parameters, concentricity, homogeneous density distribution of the explosive in all sections should also be taken into account[2].

In this paper, widespread discussion has been documented across various parameters, encompassing the type of liner geometry (conical, tulip, trumpet, hemispherical, etc.), and its impact on the performance of shaped charges.

There are many studies on these parameters. Clipii[3], who studied the standoff distance between the target and the point where the warhead is detonated, chose a standoff distance equal to 4-5 Charge Diameter (CD) for low caliber projectiles and showed that the ideal standoff distance has a very important effect on the amount of armor penetration.

Kulsirikasem[2] reported that the longest depth of penetration was reached with the copper jet compared to the depth of penetration obtained with tantalum and tungsten jets.

Vigil[4], studied jet penetration, jet tip velocities, and jet impact angles as a function of standoff distance against aluminum targets by using the LESCA code. In the study, LX-14 explosive material, aluminum liner material, and aluminum armor target were used and the jet reached its highest penetration depth with a standoff distance of 0.36-0.37 centimeter (cm), according to the size of the explosive in the shaped charge.

In Hancock's study[5], cutting speed was simulated in 3D and penetration depth was compared for different standoff distances. The best values of penetration depth were obtained with standoff distances of 5 and 8 CD diameter values of shaped charge.

Liu, Zhai, and Su[6] modeled five different-shaped charge liner designs with the LS-DYNA software package. It was reported that the design with a rounded tapered hollow-shaped charge achieved the highest penetration depth. By using round-tipped cone liner case, they achieved a 50.11 cm depth of penetration.

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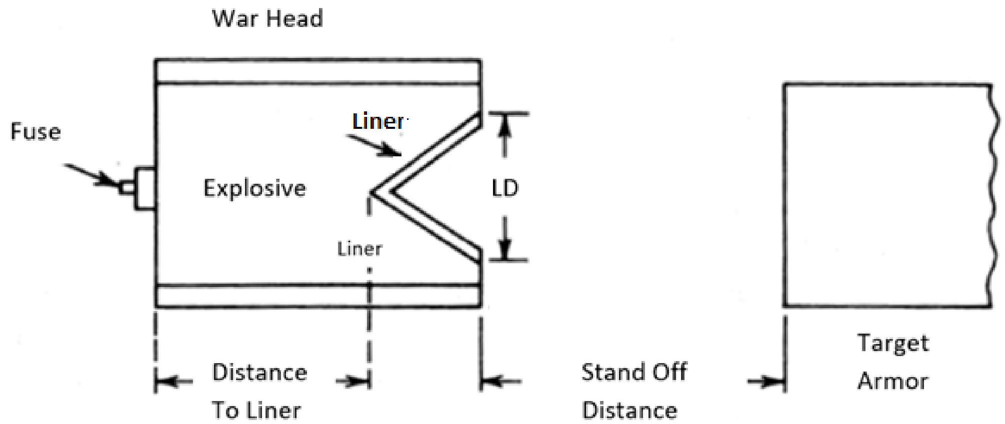

Figure 1. Shaped charge configuration[1].

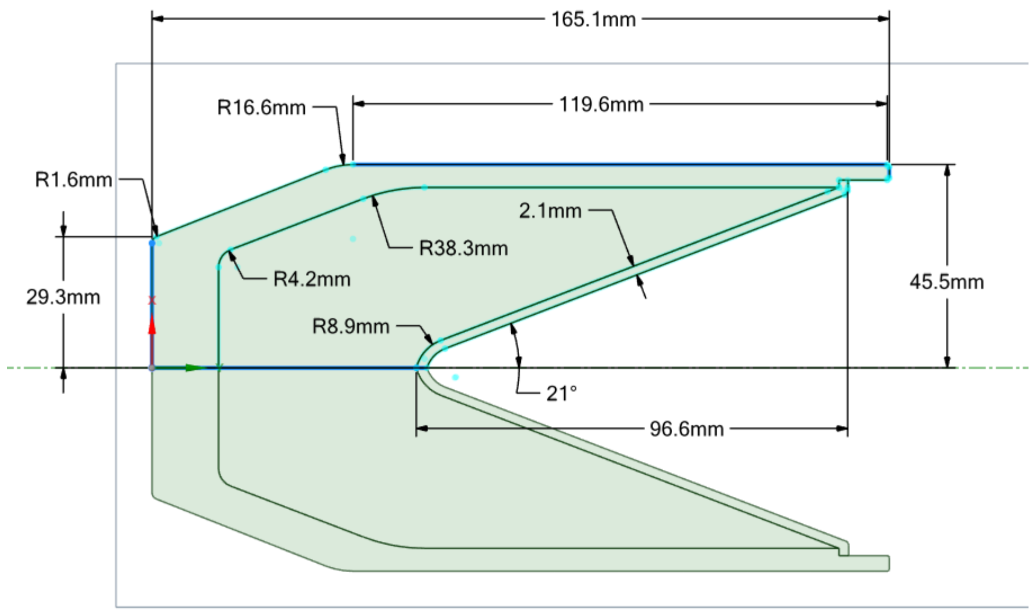

Figure 2. Overall dimensions of shaped charge warhead.

Tamer[7] reported that 100 cm penetration depth was achieved by using RDX explosive on a concrete target with a 1.5 millimeter (mm) thickness with and a 56° peak angle.

In the study conducted by Wang, Ding, and Zhao[15], experimental and numerical investigations were carried out by using three distinct shaped charge liner materials: copper, steel, and aluminum. The copper jet experiences the least unit velocity drop, resulting in the strongest penetration capability due to copper having the highest density and elongation.

Considering all these studies, the objective of this study was decided to study how the penetration depth is affected by shaped charge liner geometry while the other affecting parameters were optimized and kept constant.

2. FACTORS AFFECTING PENETRATION EFFICIENCY

When designing the shaped charge, the aim should be to reach the longest possible depth in the target armor. This requires the use of all parameters related to the penetration performance of the shaped charge. Explosive, stand-off distance, shaped charge geometry, shaped charge liner material and thickness, and material properties of the target armor are the main parameters. Penetration depth analysis was carried out on a model with overall dimensions given in Fig. 2. To investigate the effect of the shaped charge geometry on penetration depth capability, the other parameters such as standoff distance, shaped charge liner material, and its thickness were determined and kept constant.

2.1 Explosive Properties

It is stated that the explosive with higher energy produces a faster jet, more jet kinetic energy, and deeper penetration[1]. The high energy due to the explosive depends on the Gurney velocity of the explosive. The Gurney velocity increases with the detonation velocity and/or detonation pressure of the explosive, which in turn results in an increase of the jet tip velocity[7]. Gurney velocity formulas have been derived for various geometries. Among these, the Gurney velocity formula for cylindrical bodies depicting the shape charge geometry is presented in Eqn. (1).

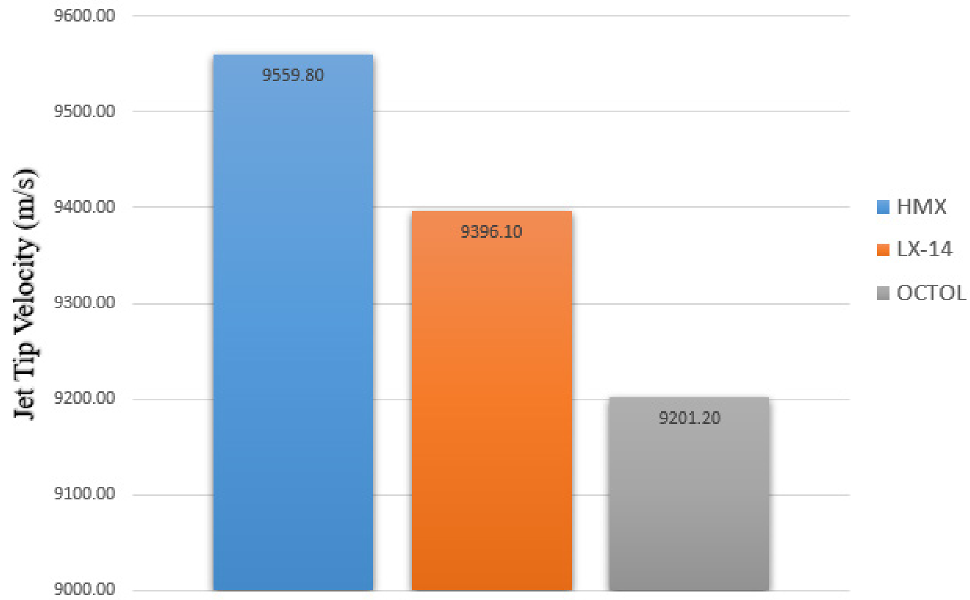

Figure 3. Jet-Tip-velocity & explosive material.

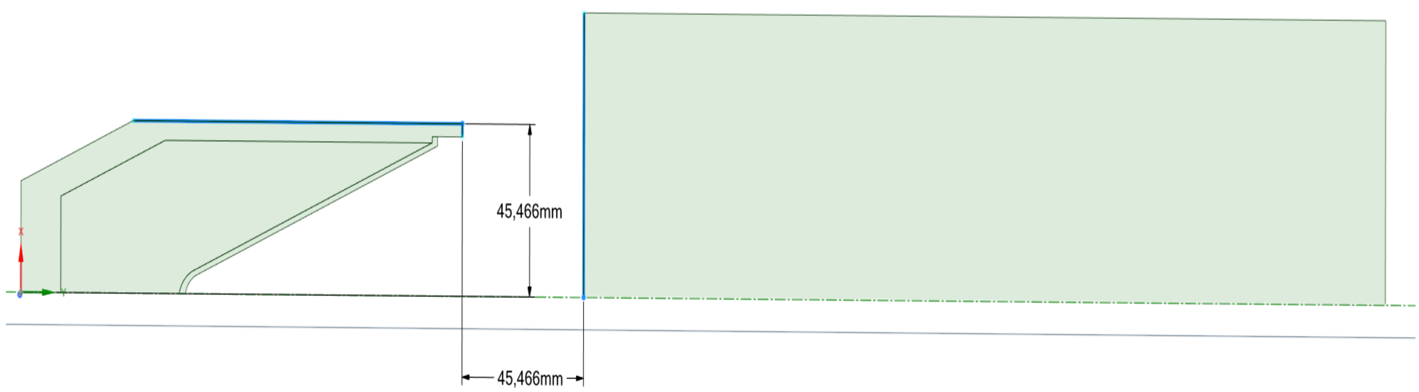

Figure 4. Model representation designed for standoff distance length (0.5 CD (45.466 mm)).

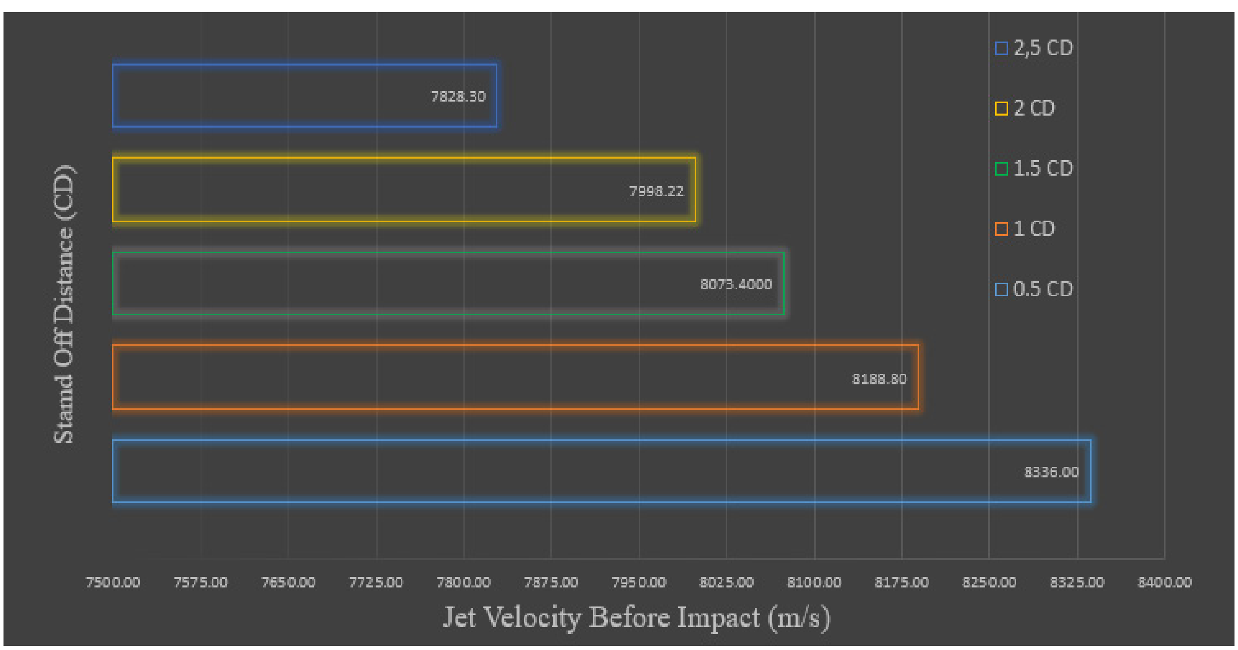

Figure 5. Jet-Tip velocity & standoff distances in CD.

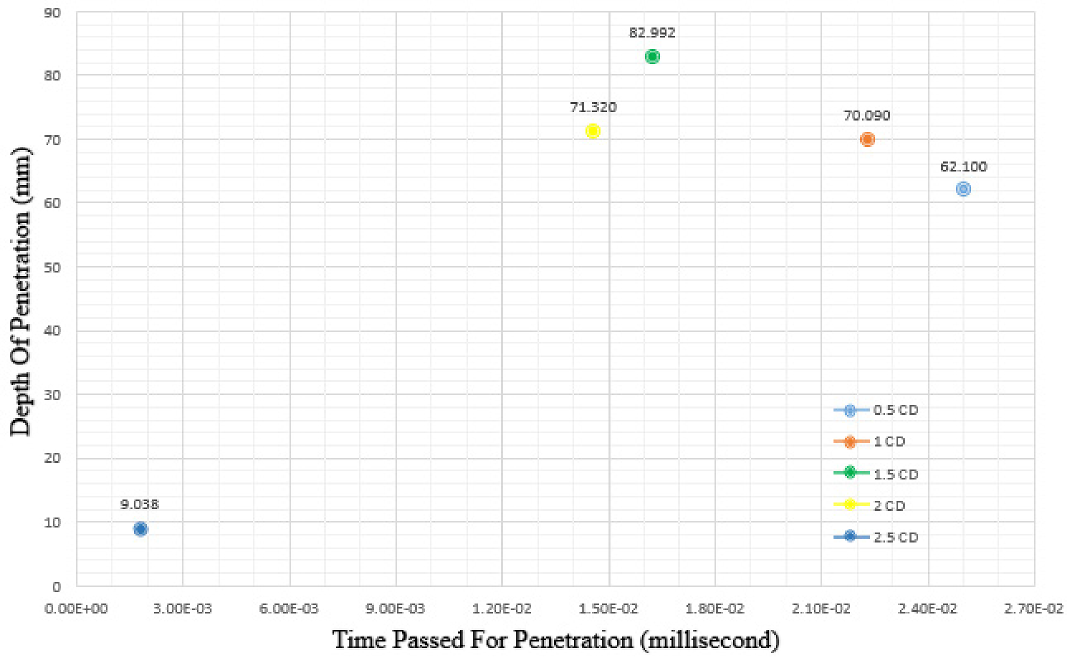

Figure 6. Penetration depth & time elapsed for penetration activity.

$$V = \sqrt{2E}\left[\frac{M}{C} + \frac{1}{2}\right]^{-\frac{1}{2}} \tag{1}$$

In the case of the cylinder, M and C represent the metal and explosive masses per unit length. The term V denotes the resulting metal velocity. E is the specific explosive kinetic energy or Gurney energy[1]. The relationship expressed in Eqn. (1) highlights that, when considering a particular explosive, the resultant metal velocity is exclusively determined by the charge-to-metal mass ratio[8].

In this paper, a computation based on Jones-Wilkins-Lee (JWL) Eqn.[9] was carried out with desensitized HMX, LX-14, and Octol explosives to find the highest jet-tipvelocity and they are shown in Fig. 3. As seen, the best jet-tip velocity was achieved by using desensitized HMX explosive material.

2.2 Stand-off Distance

In this paper; an analysis has been carried out according to different standoff distance lengths to select an ideal standoff distance. The diameter of the Shaped Charge (CD) is selected as 90.932 mm in length. Standoff distance analyses were performed by using 0.5,1,1.5,2 and 2.5 lengths in CD. Fig. 4 shows the model with a distance (standoff distance) of 0.5 in CD between the armor surface and the cone base. In the study carried out to find the ideal standoff distance, the outputs of the jet impact velocity to the armor according to the standoff distances in CD are shown in Fig.5.

According to this output, the highest jet-tip velocity is the jet with the shortest standoff distance (0.5 CD) among others.

The penetration depth in CD for different standoff distances is shown in Fig.6.

It was evaluated that there was no linear increase in the length of penetration according to the rate of increase of standoff distances. Penetration depth results according to standoff distances are given in Table 1. Based on the data obtained, it is seen that the standoff distance at which the highest penetration depth is achieved by 1.5 CD (136.398 mm).

Table 1. Penetration depth and stand-off distances

Stand-off distances [CD]	Depth of penetration [mm]	Time passed for penetration [ms]
0.5	65.3	0.02501
1	70.1	0.02228
1.5	83	0.01623
2	71.3	0.01456
2.5	9.1	0.00178

2.3 Shaped Charge Liner Material and Thickness

Although tungsten is considered the most ideal material since it has a high density beyond 19 g/cm^3, a melting point of 3410 °C, a high speed of sound, and perfect ductility, copper is generally used as the material for shaped charge liner[9]. Besides, the use of cooper is prefered for SCL since it is cheaper and easily available as compared to tungsten. Considering the jet rupture time dynamics, Copper OFHC, a material with higher yield strength than copper and aluminum, was selected as the jet material to be used in the analyses (Table 2). The Zerilli-Armstrong Material Strength Model was selected for the Copper OFHC (Oxygen-Free, High Conductivity) since it generally gives closer results to the actual tests[10].

Table 2. Yield strength values of some materials[1]

Material	Yield Strength, σ_y [MPa]
Copper	200
Copper OFHC	270
Aluminum	100

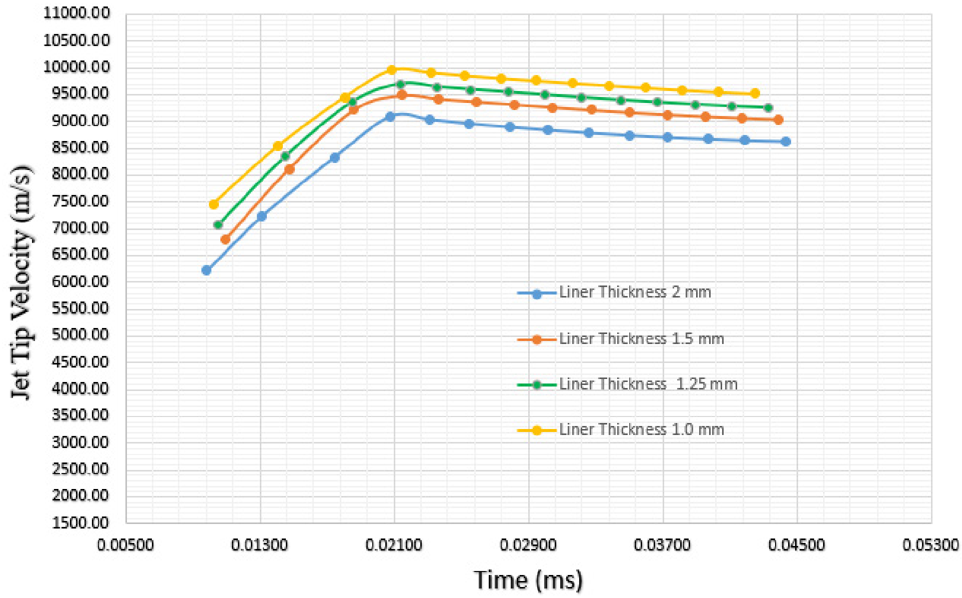

Figure 7. Jet tip velocity & time.

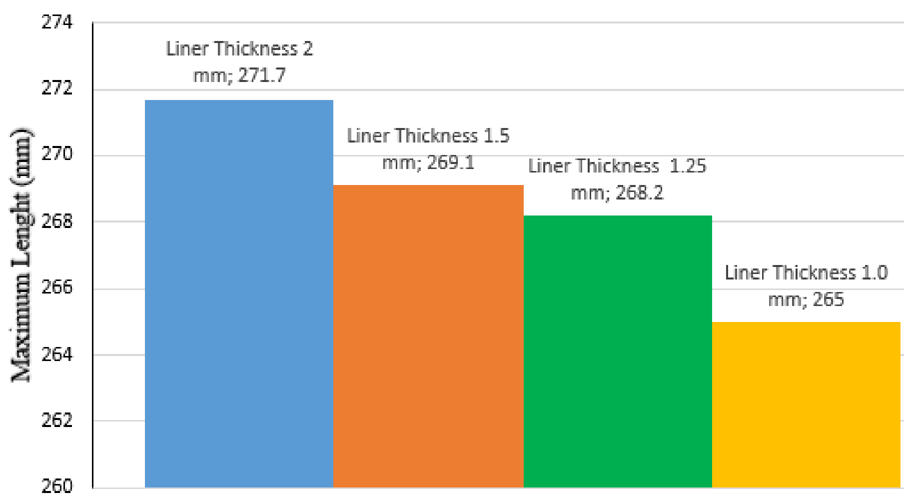

Figure 8. Maximum jet length & SCL thicknesses.

In this study, the same shaped charge geometry was used and simulations were carried out separately for different liner thicknesses in 2, 1.5, 1.25, and 1 mm each. The comparative results obtained are shown in Fig. 8-10. It is seen that the model with 1 mm thickness has the highest jet tip velocity and jet velocities commonly reach the highest velocity at 0.02 millisecond (ms) in Fig. 7. Then, the jet tip velocities decrease and constant equilibrium velocities are reached. It is also seen that the maximum jet tip velocities decrease while the jet thickness increases. The jet lengths formed according to the different thicknesses of SCL are depicted in Fig. 8. The jet length increases as the jet thickness increases.

In Fig. 9, the penetration depth against RHA armor with respect to liner thicknesses shows that maximum penetration depth might be obtained with 1.5 mm SCL thickness.

The simulation results indicate that the researchers calculated the highest maximum jet tip velocity at 1 mm SCL thickness, the maximum jet length at 2 mm SCL thickness, and the highest penetration depth at 1.5 mm SCL thickness. We see that even though an SCL thickness of 1 mm achieved the

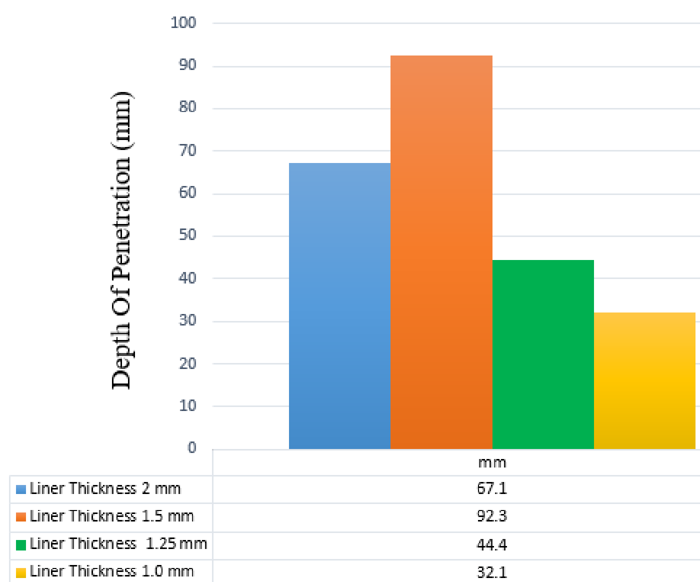

Figure 9. Penetration depth & SCL thicknesses.

highest jet tip velocity; it does not provide the best penetration depth, since considering linear momentum, the total mass of the jet (m = V. ρ) will be low.

2.4 Basic Parameters Used for the Optimal Penetration Depth

Copper OFHC was selected as the SCL material and RHA was selected as the target armor material in all simulations and parametric analyses were carried out to find the ideal penetration depth. The simulation studies according to six design parameters (DP) are summarised in the following paragraphs.

2.4.1 DP1 Simulation Study

In the study to find the numerical mesh accuracy, the highest jet tip velocity was reached in the simulation with 0.25 mm mesh size.

2.4.2 DP2 Simulation Study

Spherical erosion strain in AUTODYN options was tested for values of 1, 1.5, 2, 3, and 4, and no significant difference in penetration depth was observed.

2.4.3 DP3 Simulation Study

Copper OFHC with higher yield strength was selected as the shaped charge liner material for late jet rupture. Zerilli-Armstrong and Steinberg-Guinan material models and simulations were performed by using only hydro codes using no other model. It was confirmed by both analysis and literature studies that the Zerilli-Armstrong Model gives more realistic results for Copper OFHC.

2.4.4 DP4 Simulation Study

Shaped charge liner thicknesses of 2 mm, 1.5 mm, 1 mm, and 0.5 mm were taken and analyzed. When the maximum jet tip velocity, jet length, and penetration depth were evaluated, 1.5 mm thickness was considered to be the most optimized.

2.4.5 DP5 Simulation Study

Analyses were carried out by varying the standoff distances between the target armor and shaped charge. Among the distances of 0.5, 1, 1.5, 2, and 2.5 in terms of the diameter of shaped charge (CD), the standoff distance of 1.5 CD was found to have the highest penetration depth.

2.4.6 DP6 Simulation Study

It was aimed to find the highest jet tip velocity by changing the chemical charge material. Using desensitized HMX material, the highest jet-tip velocity reached up to 9559.9 meters per sec. (m/s).

It is very well known that the mesh structure affects the simulation results and the computation time in the numerical simulations. Since there are more elements per unit area, simulations with 0.25 mm rectangle meshes take more time than simulations with other sizes. On the other hand, jet tip average velocity differences are negligible in simulations with 2 mm, 1 mm, and 0.5 mm mesh sizes. In the simulations, the average jet-tip velocity (7799.92 m/sec) obtained with a mesh size of 0.25 mm showed 1.42 % difference in average velocities compared to the simulation result obtained with 0.5 mm mesh size (7912.07 m/s). Therefore, 0.25 mm mesh size was applied in this study.

3. MODELING AND SIMULATION

In this paper, numerical simulation in 2D is carried out by AUTODYN software package. The hydro code in the AUTODYN includes state equations and material strength model and handles mass, momentum, and energy conservation equations[11]. The target armor and the outer shell, shaped charge liner, and explosive were modeled by the Lagrange method.

The AUTODYN software package retrieves material properties from its library to input into velocity calculations during analyses. It converts the energy generated by the explosion into momentum and velocity. Calculations are conducted based on the laws of conservation of mass, momentum, and energy[11]. The computations executed within the software involve the transfer of velocity, adhering to material properties, from the initiation of the explosion to the formation of the jet and its impact on the armor.

The jet formation was modeled and simulated by using Euler solver based on continuum mechanics to obtain jet profiles at different time steps. The explosive, outer shell and shaped charge liner materials were filled with a fraction of the material in the euler solvent. It has been reported that the Euler solver is better for the early jet formation stages where large distortions caused due to the extremely high strain rate are likely to occur[12]. If a Lagrange solver is used for jet formation, it is stated that these distortions will cause the Lagrange solver to stop[7].

The Euler multi-material processor describes the blast wave propagation in the shaped charge and shows the time-dependent jet profile. The jet is allowed to move on the Euler network strings until it hits the target. The jet formed at this instant is placed back into the numerical mesh strings as a Lagrangian mass with a non-uniform velocity distribution[7].

Euler meshes are capable of large and rapid deformation where there are large distortions in gases, liquids and solids due to the fixed mesh through which the material in question flows, while the Lagrangian processor is better used for modeling solid continuum where the meshes are perturbed by the behavior of the material.

The interaction of the jet with the target armor (penetration depth) was modeled by using a Lagrange solver and a simulation study was performed based on this model.

To make the numerical resolution be handled easily, axial symmetry along the horizontal axis was assumed. As shown in Fig. 10, half of the shape charge section was drawn for modeling and a full section was prepared for simulations with the mirroring option.

The dimensions of 0.25 mm x 0.25 mm were chosen for the mesh element within the studies carried out. Fig. 11 shows the outer shell of the conical shape charge liner, the explosive, and a section of the numerical mesh cast on the shape charge liner. Modeling based on the Euler solver was used to model the vacuum environment around the parts.

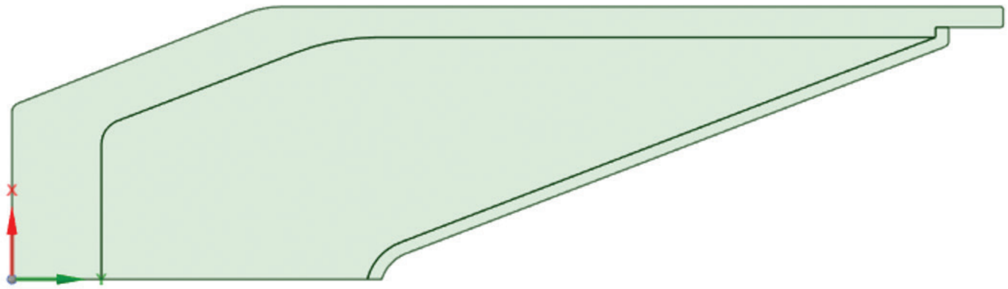

Figure 10. Typical example of shape charge cross-section.

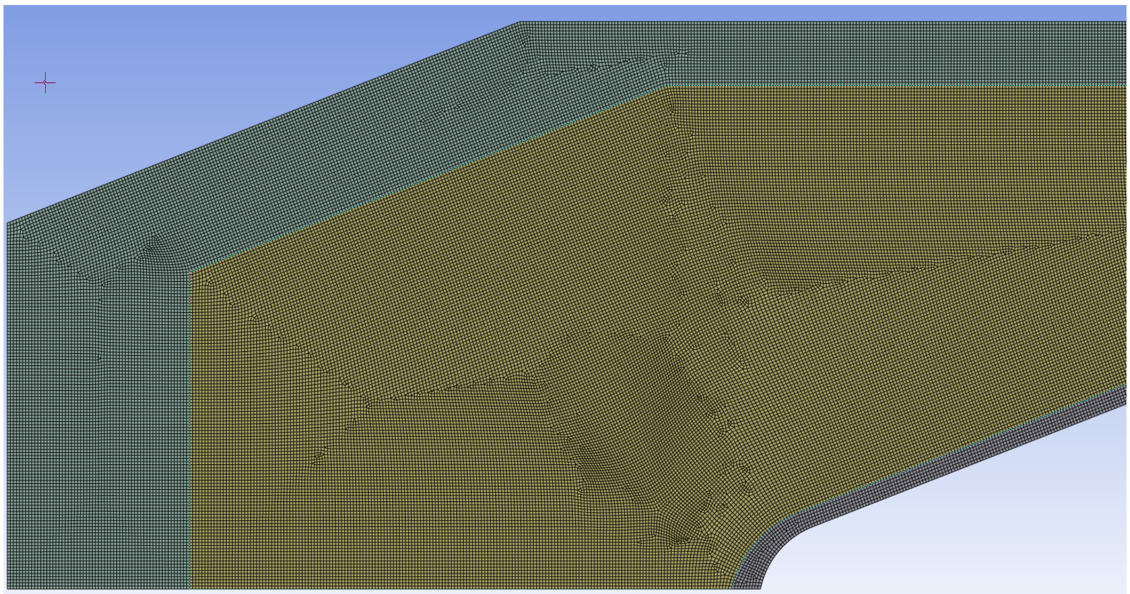

Figure 11. Mesh structure of shaped charge geometry.

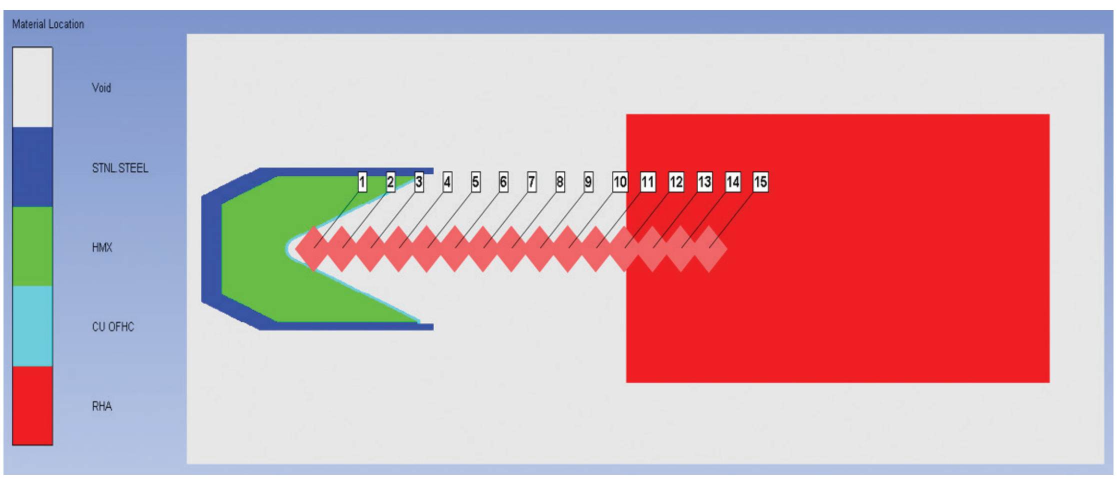

Figure 12. View of shape charge, armor and vacuum environment in AUTODYN.

The outflow boundary condition was applied to all boundaries in the solution domain except symmetry. In this way, the fragments expanded by the explosion are separated from the field without interacting with the boundaries in the solution domain[13]. Figure 12 shows the appearance of shaped charge armor and vacuum environment.

In addition, there are 15 measurement points in Fig. 12. Jet-tip velocity values can be obtained from these measurement points used in the simulation. The measurement points were arranged between 80 mm and 360 mm with an interval of 20 mm. In this study, 4 basic parts, namely the outer shell, explosive, shaped charge liner, and armor, are considered and modeled. The so-called outer shell retains the high pressure generated after the explosion and directs it toward the shaped charge liner. For the orientation to be carried out without pressure and energy loss and at high temperatures, it is appropriate to choose the outer shell from a material resistant to temperature and high pressure. Stainless steel was selected for the outer shell used in this study. In the warhead models simulated with computer programs, it is evaluated that the

Table 3. Explosive material properties[7,14]

Density [kg/m³]	Gurney speed $(2E)^{0.5}$ [mm/ms]	Material strength model	A [Pa]	B [Pa]	R_1	R_2	W	C-J explosion velocity [m/s]	C-J energy / unit mass [J/kg]	C-J pressure [Pa]
1891	2.96 mm/ms	JWL	7.78E+11	7.07E+09	4.2	1	0.3	9110	5.55E+06	4.20E+10

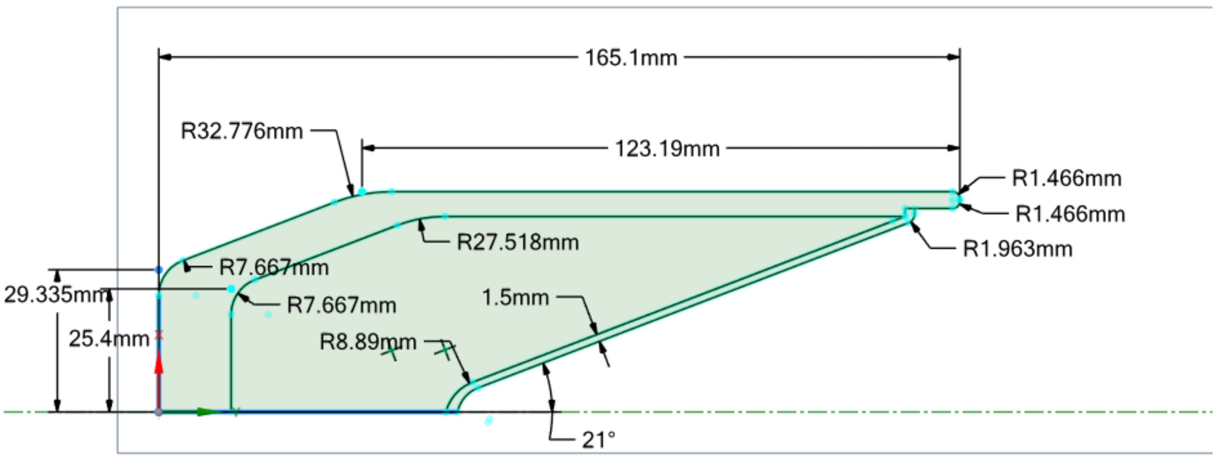

Figure 13. Dimensions of conical shaped charge geometry.

Table 4. Geometry dimensions and materials of conical shape charge liner warhead

Parts	Length [mm]	Width / radius[mm]	Material feature	Equation of State (EOS)	Material strength model	Erosion criteria
Outer shell	165.1	45.466	Stainless steel	Shock	-	-
Explosive	138.9	40.349	HMX	JWL	-	-
Conical SCL	96.61	42	Copper OFHC	Shock	Zerilli-armstrong	Instantaneous geometric strain
Armor	300	75 (half-section)	Rolled homogenous armor	Shock	Johnson cook	Instantaneous geometric strain

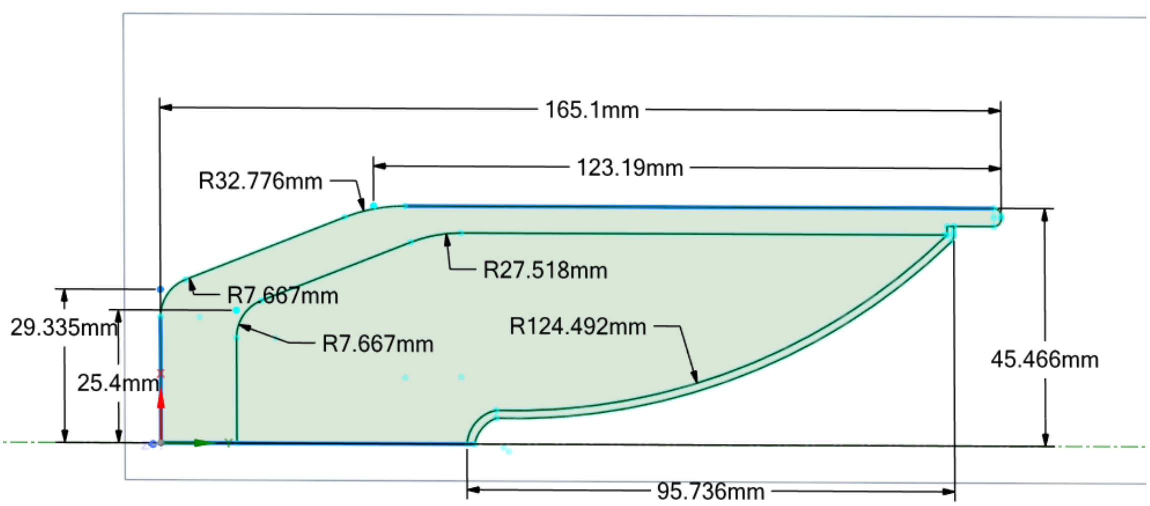

Figure 14. Dimensions of trumpet shaped charge geometry.

effect of the outer shell on warhead detonation, jet formation, and penetration depth is negligible. Therefore, the optimal penetration depth analysis for the outer shell material was not performed.

Since the highest jet-tip velocity was obtained by using desensitized HMX explosive material in the analyses carried out, desensitized HMX explosive was used for 3 different shaped charge geometry to be modelled. The properties of the desensitized HMX explosive material used in the simulations are given in Table 3.

In the study, the optimum penetration depth performance was achieved at 1.5 mm liner thickness. The thicknesses of

Table 5. Geometry measurements and materials of the warhead with trumpet shaped charge liner

Parts	Length [mm]	Width / radius [mm]	Material feature	Equation of state (EOS)	Material strength model	Erosion criteria
Outer Shell	165.1	45.466	Stainless steel	Shock	-	-
Explosive	139.6	40.349	HMX	JWL	-	-
Conical SCL	95.7	42	Copper OFHC	Shock	Zerilli-armstrong	Instantaneous geometric strain
Armor	300	75 (half-section)	Rolled homogenous armor	Shock	Johnson cook	Instantaneous geometric strain

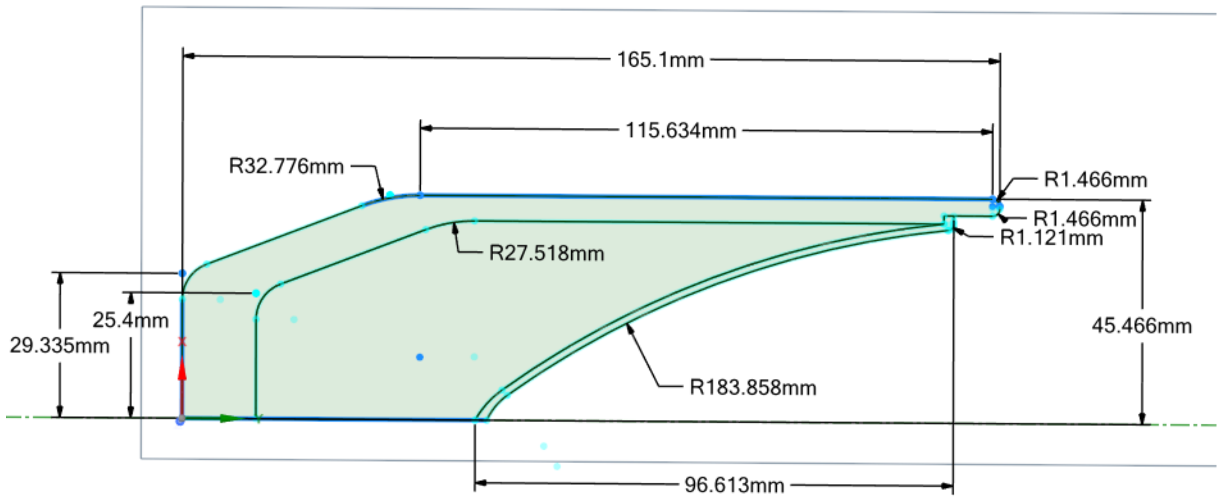

Figure 15. Dimensions of ellipsoid shaped charge.

Table 6. Geometry measurements and materials of warhead with ellipsoid shaped charge liner

Parts	Length [mm]	Width / radius [mm]	Material feature	Equation of state (EOS)	Material strength model	Erosion criteria
Outer Shell	165.1	45.466	Stainless Steel	Shock	-	-
Explosive	138.9	40.349	HMX	JWL	-	-
Conical SCL	96.6	42	Copper OFHC	Shock	Zerilli-Armstrong	Instantaneous geometric strain
Armor	300	75 (half-section)	Rolled homogenous armor	Shock	Johnson Cook	Instantaneous geometric strain

Conical, Trumpet and Ellipsoid SCLs were selected as 1.5 mm and Copper OFHC was selected as SCL material as described previously.

The standoff distance between the conical SCL of Shaped Charge and the Armor was modeled as 1.5 times the diameter value (CD) of the Conical Shaped Charge, which, as determined, is 136.398 mm.

In this study, RHA steel was selected as the material for the armor. Johnson Cook material strength model was selected for RHA armor material. This model determines the relationship between strain and stress and the relationship between strain rate and stress[14].

3.1 Conical Shaped Charge Model

The Conical Shaped Charge Model used in this study is shown in Fig. 13. Here, the dimensions of half of the cross-section of the model are shown. The parts used in this designed shaped charge model, part dimensions, material properties and similar other information are given in Table 4.

3.2 Trumpet Shaped Charge Model

Trumpet shaped charge model in this study is depicted in Fig.14. Here, the dimensions of half of the cross-section are shown.

The parts, part dimensions, material properties, and other information used in this designed-shaped charge model are given in Table 5.

3.3 Ellipsoid Shaped Charge Model

Ellipsoid shaped charge model in this study is shown in Fig. 15. Here, the dimensions of half of the cross-section are shown. The parts used in this designed shaped charge model, part dimensions, material properties, and similar other information are given in Table 6.

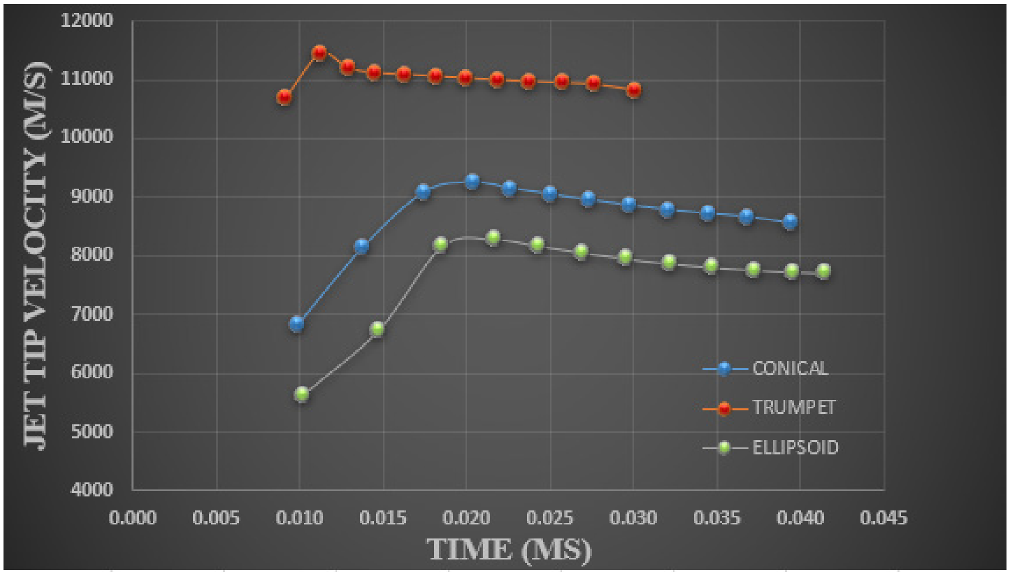

Figure 16. Simulation outputs of shaped charge with conical, trumpet and ellipsoid geometry.

4. SIMULATION RESULTS AND DISCUSSION

The graphic of the jet-tip velocities of the conical, trumpet and ellipsoid-shaped charges versus the time from the beginning of the explosion until the armor impact is shown in Fig. 16. The values of the highest jet tip and slug velocities are given in Table 7. The surface area of the SCL with trumpet geometry is smaller than the SCL with conical geometry. This means that the trumpet SCL with trumpet geometry is capable of absorbing more energy from the explosive, although they have approximately the same total mass in both geometries. Due to the fact that the surface area of the SCL with trumpet geometry liner is smaller than that of the SCL with conical geometry liner, the amount of explosive material behind the SCL is higher within the same dimensions of the length and width of the shaped charge. As a result, higher jet tip velocities were achieved with the SCL with trumpet geometry.

The maximum jet lengths and the largest diameters of the jets formed before impacting the armor and shown in Fig. 17 are given in Table 8.

Table 7. Jet velocity data in simulations

Shaped charge designs	Highest jet tip velocities [m/s]	Slug velocities [m/s]
Conical	9240.7	214
Trumpet	11437.1	147
Ellipsoid	8286.8	168

Table 8. Jet length and diameter values achieved in simulations

Shaped charge designs	Jet length[mm]	Largest diameter [mm]
Conical	229.5	25.9
Trumpet	232.0	17.9
Ellipsoid	223.9	34.9

As can be seen in Fig. 17, the mass "Slug" at the rear of the jet is formed in the largest width in the Ellipsoid SCL and the least width in the Trumpet SCL. Thus, it is evaluated that the jet formed in the Trumpet SCL has a good stretch and the majority of the mass forming the jet moves at high speeds.

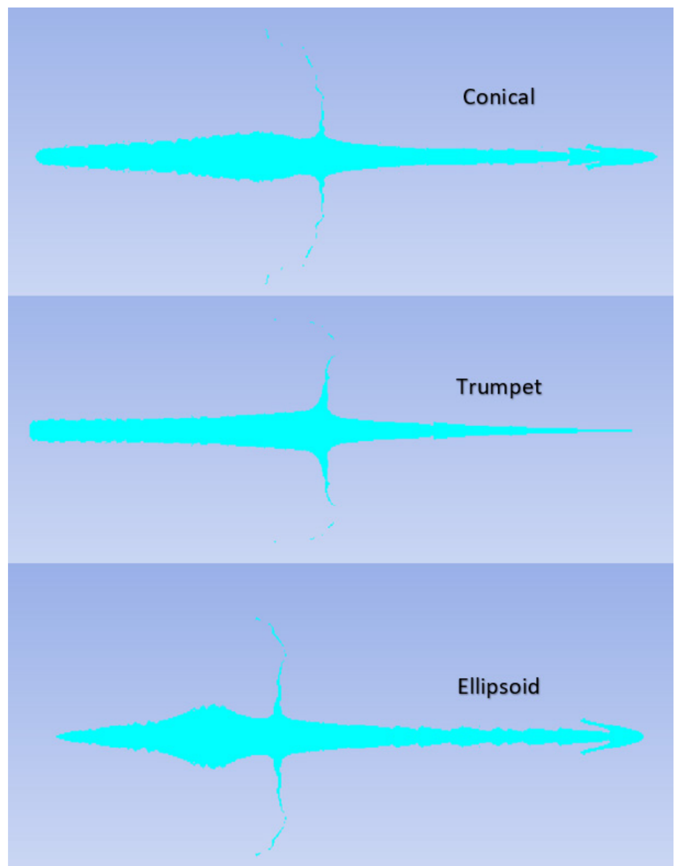

Figure 17. Conical, trumpet and ellipsoid shaped charge jet.

As a result of the simulations with 3 different shape charges, the data on the penetration depth on RHA armor are listed in Table 9 and depicted in Fig. 18. The numerical results showed that the SCL with trumpet geometry increased the penetration depth by 43.98 % compared to the SCL with conical geometry.

Table 9. Penetration effectiveness values occurred in target armor

Shaped charge design	Penetration depth [mm]	Hole diameter [mm]	Completion time of penetration activity [ms]
Conical	48.5	14.2	0.0601
Trumpet	69.8	12.2	0.0601
Ellipsoid	19.8	16.4	0.0601

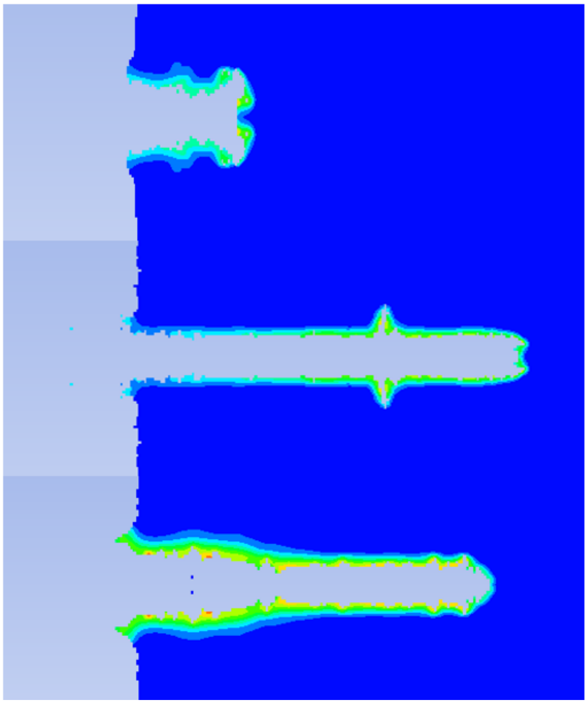

Figure 18. Armor penetration effectiveness of ellipsoid, trumpet and conical shaped charge (from top to bottom in order).

5. CONCLUSION

In this article, studies have been done to increase the penetration depth of shaped charge by modeling them with different shaped charge geometries. To find the optimum penetration depth, similar studies in the literature have been reviewed, basic theories on system dynamics have been summarized, and some simulations have been carried out to determine which parameters should be selected for the optimization of the penetration depth and how to select the basic materials that form the shaped charges. The results available in the literature and the models used in this study were verified by using AUTODYN software package.

In simulations performed to find the most effective explosive material to be used, it was observed that the highest jet-tip velocity of 9559.80 m/s was achieved when desensitised HMX explosive material was used. The ideal standoff distance between the target armor and the shaped charge was chosen to be 1.5 CD (136.398 mm) in terms of the diameter of the shaped charge. With an ideal thickness of 1.5 mm and trumpet geometry of shaped charge, a penetration depth of 69.775 mm in 0.0601 ms was achieved.

Shaped charges with conical, trumpet and ellipsoid SCLs were selected and modeled by using the parameters obtained from the best penetration depth analyses. In the simulations performed with AUTODYN using these parameters, it was concluded that the highest jet-tip velocity, the longest penetration depth, and jet length were achieved with the trumpet shaped charge design, and the largest hole diameter was achieved with the Ellipsoid Shaped Charge Design.

Considering these results, the evaluation suggests that if high penetration depth is desired in the armor; it is appropriate to design a shaped charge with Trumpet SCL geometry, and if a large hole is desired in the armor, it is appropriate to design a shaped charge with Ellipsoid SCL geometry.

Ascribing the attainment of greater jet velocity and consequently increased penetration solely to the extended length of the explosive head behind the cone apex may not be the exclusive factor. In the trumpet-shaped charge configuration, the explosive mass behind the entire liner is greater. According to Gurney's postulation and can be seen in Eqn. 1, a higher ratio of explosive mass to metal mass leads to higher particle velocity. Also as shown as in Fig. 17, trumpet liners are noted for yielding elevated jet velocities and reduced inverse velocities.

In this article, 2D geometries were used in modeling, numerical meshing, and simulation studies.

Modeling was performed for half of the warhead sections from the middle part and simulation studies were carried out in a computer environment with a medium-level processor. If modeling and simulation can be performed with more powerful processors, more precise results can be obtained as it will be possible to throw the digital network at smaller scales.

In addition, analyses were not performed by changing the angle of the peak point of the SCL and the length of the SCL. Investigation of the penetration effect when these parameters are changed can be considered as a separate study. In addition, it is recommended to carry out modeling and simulation studies in 3 dimensions instead of 2 dimensions.

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CONTRIBUTORS

Mr Kerem Can Albayrak is an Engineer in Defense Industry Agency, Türkiye where he is involved in Missile projects. He has done Master of Science on shape charge penetration. In the present study, he has contributed in terms of researching, making penetration analyses in software and conducting literature surveys.

Dr Murat Üçüncü is an Assistant Professor in Electrical and Electronics Engineering Department, Baskent University, Turkey. He is also acting as the Chairman of Defense Systems and Technologies in Institute of Science and Engineering at the same university. His research areas are Defense systems, automated control systems and telecommunication.
He contributed in the current manuscript in terms of developing, coordinating and guiding the overall research.

Dr Faruk Elaldi is a Professor and Head of the Institute of Science and Engineering, Baskent University, Turkey. He obtained his PhD from Middle East Technical University, Turkey. His research areas are: Ballistics, impact mechanics, solid mechanics and composite armor.
In the current study, he has provided guidance for the discussions on the obtained results of shaped charge penetration using numerical methodology.