Numerical Analysis of The Crater Diameter and Penetration Depth of The Target Due to The Impact of Short-Rod Segmented Projectiles at High Velocity

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Abstract: This paper deals with the numerical simulation of segmented projectiles. A segmented projectile is a subset of kinetic energy projectiles. The segmented projectile is made of tungsten and the target is semi-infinite and is made of 4340 steels. Due to the disadvantages of segmented projectiles with, the simulation of segmented projectile with is discussed. Projectiles with aspect ratio greater than one are known as short-rod projectiles. This aspect ratio range forms both the primary and secondary phase of penetration. Numerical simulation was performed by AUTODYN software with Smoothed Particle Hydrodynamic (SPH) method. The use of SPH approach is most consistent with the experimental results. In order to have effective segmented projectiles, greater speeds were used in the simulations. In this range of velocity, due to the hydrodynamic penetration and complete erosion of the rods, the maximum penetration depth is obtained. After a relatively good correlation between the simulation results and the experimental and Hydrocode results, the numerical analysis of the segmented projectiles is performed. The results show an increase in the penetration depth of segmented projectile relative to the continuous type. In the following, the relationship between velocity increase and penetration depth and crater diameter of this type of projectile is investigated. An increase in penetration depth of 40 to 60% has been observed in this type of projectile compared to the continuous projectiles. An increase in penetration depth and crater diameter is observed with increasing impact velocity.

Keywords: Aspect Ratio, Numerical Simulation, SPH, Segmented Projectile

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1 INTRODUCTION

In recent decades, studies have begun on a new generation of projectiles known as kinetic energy projectiles that have high penetrating power. The penetration power of this type of projectiles is due to its high velocity and density. A subset of kinetic energy projectiles is segmented projectiles. The performance of segmented projectiles in dealing with different targets has been considered. Experiments and numerical simulated computations performed on continuous projectiles show that at high velocities, projectiles with a lower aspect ratio (L/D) were compared with higher aspect ratio, they have more specific efficiency (P/L). These results led researchers to use projectiles with smaller (L/D) and alignment whose total length and mass are equal to the corresponding continuous projectiles.

It was like that an continuous projectile is divided into smaller, coaxial projectiles, thus reducing (L/D) each segment [1], the penetration efficiency of segmented projectiles has been reported to be 40 to 300% if the launch and impact conditions are ideal. Penetration efficiency (P/L) refers to the ratio of penetration depth to the initial length of the projectile. L for a segmented projectile is the sum of the lengths of the segments [2], Naz and Lehr [3], investigated simulation of segmented projectiles into steel targets at velocities from 2 Km/s to 5 Km/s .

In this simulation, HULL code is used. In this study, due to the high velocity of the projectiles, a secondary phase of penetration has been added for each segment, so a segmented projectile has a greater penetration depth than a continuous projectile with equal diameter and mass. Christman and Gehring [4] further showed that the penetration depth of the primary penetration phase is proportional to the length of the projectile and the secondary phase is independent of the length. Lee and Normandia [5] studied segmented projectiles with aspect ratio ($1/8 \le L/D \le 1$) that are known as small aspect ratios. In this study, it was shown that for segments with $L/D < 1$, the penetration depth is constantly decreasing for each segment. This was due to the existence of the remaining of previous segments in the crater and this factor is significant for small aspect ratios.

Holland and et al. [6] performed a hydrocode computation and results was compared with experimental results. In this study, various structures of the projectiles such as ideal segmented projectiles with various distances, the corresponding hybrid projectile with axial spacers, and continuous projectiles of various diameters have been investigated. It was shown that the shape of the crater created by continuous projectiles is smooth while in segmented projectiles; the shape of the crater is scalloped. This is due to successive impacts of segmented projectiles. Mchenry et al [7] investigated numerical analysis of aluminum projectiles with various L/D . In this study, they examined the penetration depth of the projectile with parametric variations in the projectile length to diameter ratio ($1/2 \le L/D \le 10$) and impact velocity ($1 \le V \le 6\,km/s$). They compared the numerical results with the results of Tate penetration model and the experimental data. It was found that the numerical results are in good agreement with the experimental data whilst the results did not match the Tate model. The reason is the tendency of the Tate model to over-predict the after-flow penetration and crater diameter for low L/D values and high velocities.

Lee [8] made a comparison with the numerical simulation approach of continuous projectile and segmented type into fixed and moving targets. Lee showed that continuous projectiles into moving oblique Targets are more efficient than segmented projectiles and segmented projectiles perform slightly better than continuous projectiles into fixed targets. It was also shown that segmented projectiles have a significant penetration performance compared to continuous projectiles at velocities greater than $2000\,m/s$.

Aly and Li [9] investigated Numerical simulation of the article [10] using AUTODYN numerical code at velocities from $1.3\,km/s$ to $4.2\,km/s$. The purpose of this simulation is to find the contribution of the penetration of carrier tube and filler between segments in the penetration of the non-idea segmented projectiles. The performance of this type of projectile is higher than its ideal type in terms of penetration depth. In segmented projectiles, there is a transient impact velocity greater than that velocity, increasing the penetration depth is achieved by a segmented projectile.

This research showed that there is a good match between the numerical results obtained from AUTODYN and the experimental values reported. Hegde et al. [11] investigated the hydrodynamic impact velocity for different projectile and target combinations. They showed that the penetration performance has a maximum value when interaction between the projectile and the target is hydrodynamic. Considering negligible strength of the target and the projectile in high velocities, hydrodynamic impact velocity can be predicted using the hydrodynamic equation of state.

This study showed that Allen and Roger's experimental work was invaluable in ignoring projectile strength at high velocities. Cao et al. [12] numerically investigated the penetration of a segmented projectile with various connectors. In this study, this was a numerical simulation work. Tungsten alloy segmented projectiles into semi-infinite steel target at velocities from $1.5\,km/s$

to $3.1 km/s$ are investigated. AUTODYN code with SPH solver is used. They showed that the use of SPH method is most consistent with the experimental data. In a study, Presnell and Rajendran [13] investigated the numerical analysis of the penetration of tungsten projectiles into steel targets at high velocities.

In this article, the 2006 version of Lagrangian finite element code EPIC is used. Its purpose is to investigate the phenomenon of flowing ejecta material using this code. Also, the results of EPIC are compared with the results of AUTODYN code. Zolfaghari and Miraghaie [14] presented a mathematical model for the penetration of a segmented projectile into semi-infinite ceramic target. The factors of velocity, segments length, segments distance and number of segments are investigated. The results showed that the impact velocity is the most important factor in increasing the penetration depth. Unlike the penetration mechanics of continuous projectiles, there was no hydrodynamic limit velocity for the penetration of segmented projectiles into semi-infinite targets and the increase rate of penetration depth is corresponding to increasing velocity for velocities greater than $2500 m/s$.

Arjangi et al [15] studied the simulation of rock drilling process by the SPH method. Given that simulation and modelling of the cutting process is a complex issue and various methods have been suggested for it. They mechanically analyzed the drilling process by the SPH method. In this analysis, they used LS-DYNA software. Hedayati and Vahedi [16] used ABAQUS software with a smooth particle hydrodynamic approach to evaluate the accuracy of their corrective analytical model. The results show that the data obtained from the SPH method are more accurate than the Florence analytical model that confirm the corrective analytical model.

Frissane et al. [17] used the smooth particle hydrodynamics method to simulate high velocity projectiles with flat nose into metal targets. To reduce the computation time, which is important in the SPH method, a developed solver called a graphics processing unit has been used. These speeds up the simulation time and allows us to use a large number of particles (2-8 million).

Giannaros et al. [18] investigated the behaviour of carbon fibre reinforced polymer composites under hypervelocity impact of aluminium projectiles and secondary debris formed during the penetration process on the target using LS-DYNA code with a smooth particle hydrodynamic method. The purpose of this study is the effect of parameters used in SPH on the impact behaviour of materials.

In this research, the ratio L/D that is important in relation to decreasing or increasing the penetration depth in segmented projectiles has been investigated. Due to the disadvantages of segmented projectile with $L/D \leq 1$, such as alignment problems during launch, the existence of the remaining segments at the bottom of the crater, less research has been done in ratio $1 < L/D < 4$, etc. segmented projectiles with $L/D > 1$ have been examined. In this paper, the effect of segmented projectiles with aspect ratio ($L/D = 2,3,4$) on the penetration depth and their comparison with continuous projectiles is investigated. Also, in the other part of this paper the penetration depth and the diameter of the crater for this ratio at velocities from $2.5 km/s$ to $4 km/s$ have been examined. Also, in numerical simulations the smooth particle hydrodynamics approach is used which this method as Lagrangian mesh free and it is applicable to high velocity and large deformation analysis like impact and penetration behaviour. The SPH approach is most consistent with the analytical solution and experimental results.

2 SMOOTH PARTICLE HYDRODYNAMIC METHOD

Computer simulation has increasingly become an important tool for solving practical and complex problems in engineering and science. Simulation plays a prominent role in providing tests and experiments for theories. It also helps to clarify the complex physics of the problem and to interpret and discover new phenomena. Problems and limitations of meshing-based methods are especially evident when simulating hydrodynamic phenomena such as explosions and high velocity impacts.

During the explosion process, phenomena such as large deformations, large heterogeneities, displacement of material interfaces, deformable boundaries, and free surfaces are observed. These specific phenomena pose great challenges for grid-based numerical simulations. High velocity impact problems, including the propagation of shock waves caused by impact on the body, behave like fluids. Over the years, major research has focused on meshless methods towards efficient generation of computational methods for solving complex problems. A distinct mesh-free method is the particle hydrodynamic method.

In SPH, the state of a system is expressed by a set of particles that have material properties and interact with each other in a range controlled by a weight function or a smooth function. Examples of the application of the SPH method in high energy processes include explosion, underwater explosion, high velocity impact, and penetration phenomena [19]. In the meshless analytical method, unlike the finite element method, there is no need to define a standard element to describe physical behaviour. Instead, in this method, a set of nodes replaces the mesh or grid elements [20].

3 NUMERICAL SIMULATIONS

In this paper, AUTODYN finite element software is used for numerical simulation. After validation of the simulation, segmented projectiles with different aspect ratios (L/D) have been investigated. The projectile is made of tungsten and the target is made of 4340 steels. Since the simulation results are validated with results [6], the projectile and target behavioural models such as state equation and strength model have been selected as [6]. The equation of state, which shows the relationship between pressure and volume change or density, is linear. The strength of the material, which indicates the relationship between stress-strain [21], the onset of yield and the flow of matter, Von Mises type is considered. The dimensions of the projectile are considered the same as in [6]. The diameter of each segment (D) is 5.54 mm. (L) is the length of each segment. In order to keep the target constant, both the initial and the boundary conditions are considered in two directions x and y equal zero. The dimensions of the target are considered in such a way that its lateral dimensions and back surface do not affect the penetration process. In this case, the target can be considered semi-infinite ("Fig. 1").

3.1. Validation

In this section, the validity of the results of Autodyn simulation with the article [6] where a hydrocode computational work is performed and compared with the experimental test results is first discussed. A section of article [5] investigated the simulation of the impact of different projectile structures made of tungsten alloy with a target made of 4340 steels. The parameters of the material properties are given in "Table 1".

In all simulations performed by Autodyn in this paper, the meshless approach (SPH) is used. In the following, simulations are performed by Autodyn software and their comparison with the results in the article [6]. First, the values obtained for the continuous projectile are considered. As shown in "Table 2", the obtained results are in good agreement with the results of article [6]. Figure 2 shows the penetration of a continuous projectile with ($L/D=5$) at velocity $2550\,m/s$.

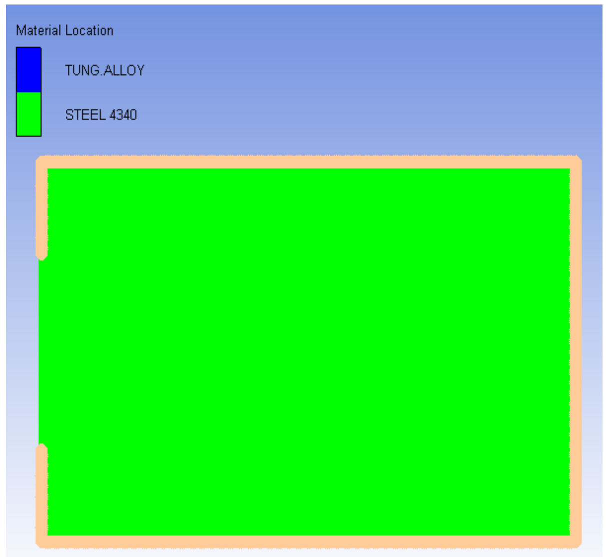

Fig. 1 Semi-infinite target with boundary conditions.

Table 1 Mechanical property of the projectile and the target

	Tungsten w-10	Steel 4340
Equation of State	Linear	Linear
Density, gr/cm^3	17	7.84
Bulk Modulus, Kpa	3.313×10^8	1.83×10^8
Shear Modulus, Kpa	1.60514×10^8	0.704864×10^8
Yield Stress, Kpa	0.006467×10^8	0.010×10^8

Table 2 The depth of penetration (DoP) obtained for the continuous projectile at $2550\,m/s$

	Diameter,mm	Mass, gr	DoP, mm [5]	DoP experiment, mm [5]	DoP AutoDYN ,mm
$L/D=5$	5.54	11.35	41	42	39.07
$L/D=13$	5.54	29.51	93	N/A	87.611
$L/D=19.5$	3.69	13.06	85	N/A	85.359

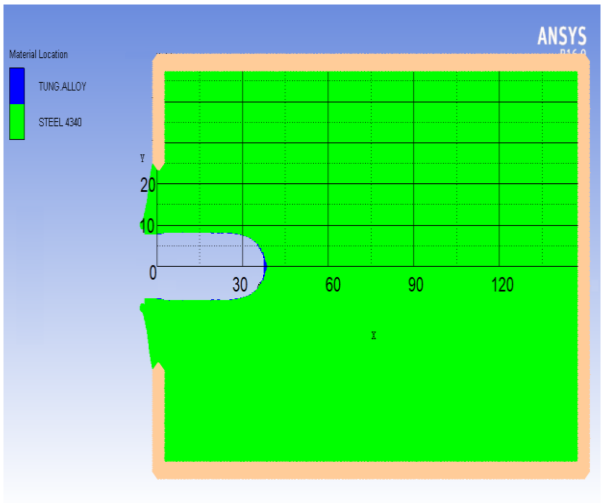

Fig. 2 The continuous projectile penetration depth with $L/D = 5$ and $V = 2550\,m/s$.

Figure 3 shows the same projectile with $L/D = 13$ and $V = 2550\,m/s$. As shown in “Fig. 2” and “Fig. 3”, with increasing L/D , an increase in penetration depth and a decrease in penetration crater diameter have been observed.

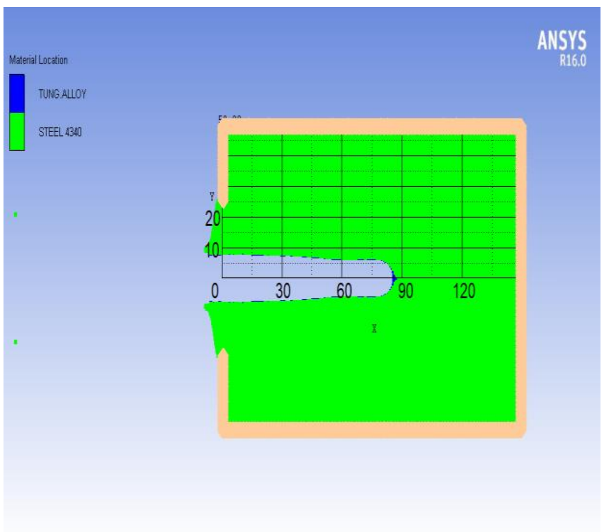

Fig. 3 The continuous projectile penetration depth with $L/D = 13$ and $V = 2550\,m/s$.

In “Fig. 4”, the diameter of the hole of the crater becomes smaller, which is related to the decrease in the diameter of the projectile. Also, for $L/D = 19.5$, it has a reduction in projectile mass, which reduces the penetration depth.
Then, “Table 3” compares the results of the SPH approach for segmented projectiles with the results of article [6].

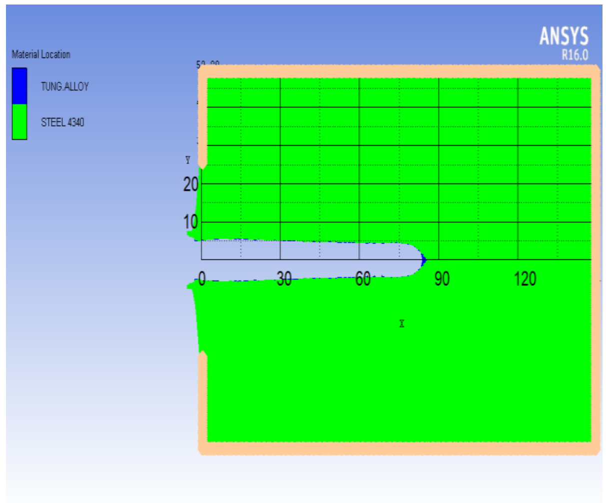

Fig. 4 The continuous projectile penetration depth with $L/D = 19.5$ and $V = 2550\,m/s$.

Table 3 Depth of penetration obtained for segmented projectile with $L/D = 1$ at $2550\,m/s$

	Segment Spacing	DoP, mm [5]	DoP, mm
$5L/D = 1$	$S/D = 1$	46	49.854
$5L/D = 1$	$S/D = 2$	54	52.735
$5L/D = 1$	$S/D = 3$	N/A	53.229

3.2. Numerical Solution for A Segmented Projectile with Various Values

After validation of the results obtained from numerical simulation, the impact of segmented projectiles and the comparison of the penetration depth obtained with the continuous projectile have been investigated. Segmented projectiles with $L/D = 2,3,4$ have been compared with continuous type with $L/D = 12$. In this simulation, the velocity is $4500\,m/s$ and diameter is 5.54 mm. Finally, the penetration depth and the diameter of the crater created by this type of projectile at $2500 \le V \le 4000\,m/s$ are investigated.

4 RESULTS AND DISCUSSION

In the simulation shown in “Table 4”, a continuous projectile with $L/D = 12$ at velocity $4500\,m/s$ is considered. Then, by changing the geometric structure and turning it into segmented projectiles, the penetration depth is calculated. With the observations obtained from the simulations [8], a distance equal to the length of segments, it is necessary for the distance between the segments that each segment penetrates the target separately. Of course, there is an optimal distance that depends on the velocity of the segments and aspect ratio, which is not discussed in this article. “Table 4” shows an approximate 40 to 60% increase in the penetration depth of a segmented projectile compared with a continuous type. With increasing number of segments and decreasing L/D, increasing penetration depth has been observed.

Table 4 Depth of penetration for segmented and continuous projectiles at velocity $4500\,m/s$

	DoP, mm	Increase %
$L/D=12$	79.966	
$6\ L/D=2$	126.37	%58
$4\ L/D=3$	118.59	%48
$3\ L/D=4$	111.84	%39

Figure 5 shows the crater created by the impact of a continuous projectile at velocity $4500\,m/s$. The diameter of the crater is larger than the diameter of the crater created by the segmented type. Also, the crater wall is completely smooth.

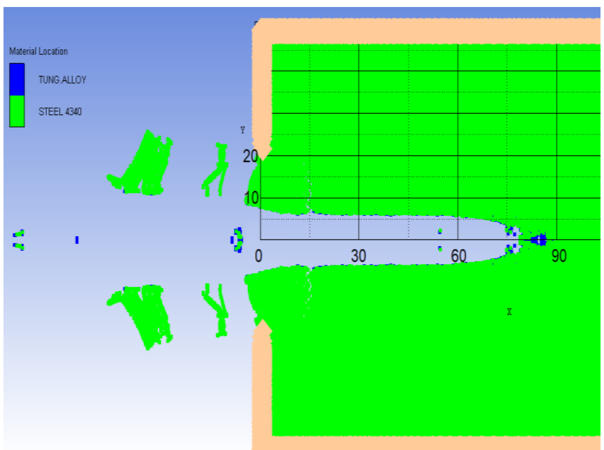

Fig. 5 The crater shape for $L/D=12$ and $V=4500\,m/s$.

Figure 6 shows the crater created by segmented projectile ($6\ L/D=2$) at velocity $V=4500\,m/s$. The scalloped shape profile of the crater is clearly visible relative to the smooth shape of the crater created by the continuous type. This scalloped shape is due to the nature of multiple collisions of a segmented projectile. Also, the largest size of the crater diameter is created by the first and last segment. There is a lot of reversibility in the target when penetrating these types of projectiles, which can be due to the momentum, high pressure and temperature that occur in the target in high velocity impacts.

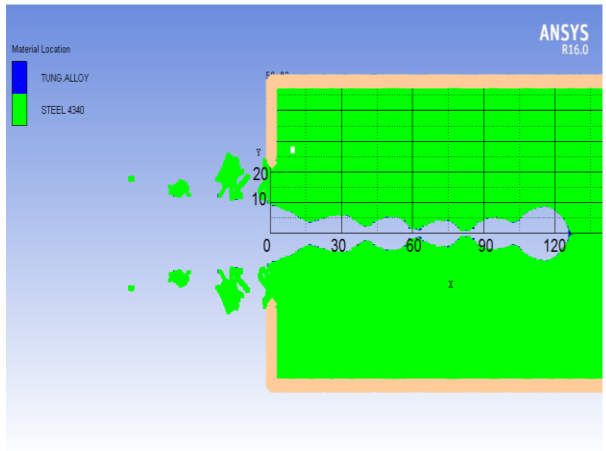

Fig. 6 The crater shape for $6\ L/D=2$ and $V=4500\,m/s$.

Figure 7 shows the crater created by ($4\ L/D=3$) at the same velocity, which shows an increase in penetration depth in the impact of each segment compared to “Fig. 6”. This is due to the increase in the penetration contribution of the primary phase of the segments, which increases with increasing aspect ratio (L/D).

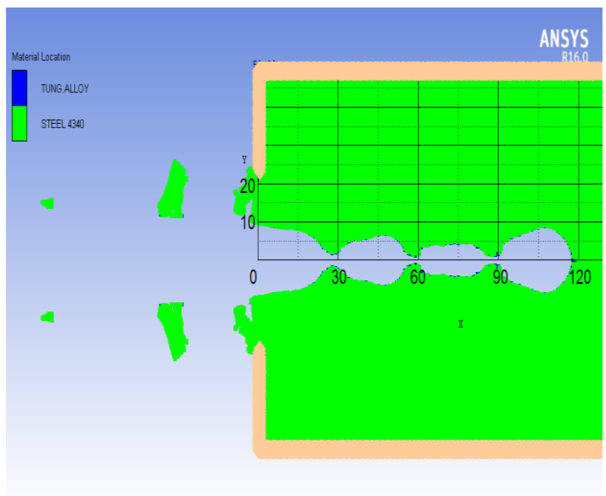

Fig. 7 The crater shape for $4\ L/D=3$ and $V=4500\,m/s$.

Figure 8 shows the shape created by ($3\ L/D=4$) at $V=4500\,m/s$ in which the boundary between the craters closes, which is due to the reversibility of the target material due to the high velocity of the impact. At high velocities, due to the high pressure that is created, the material reaches the melting point and it takes on a fluid state. Figure 9 shows the penetration depth for a segmented projectile with different aspect ratios at velocities $2500 \le V \le 4000\,m/s$. As the velocity increases, the penetration depth increases. Also, as the number of segments increases, the penetration depth increases. As this difference in penetration depth is more visible at high velocities.

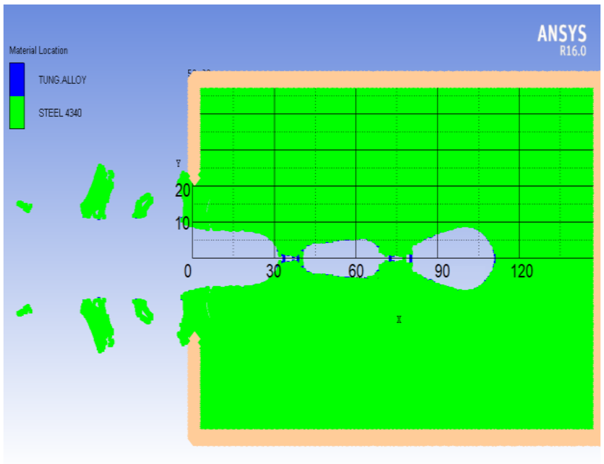

Fig. 8 The crater shape for $3\ L/D = 4$ and $V = 4500\,m/s$.

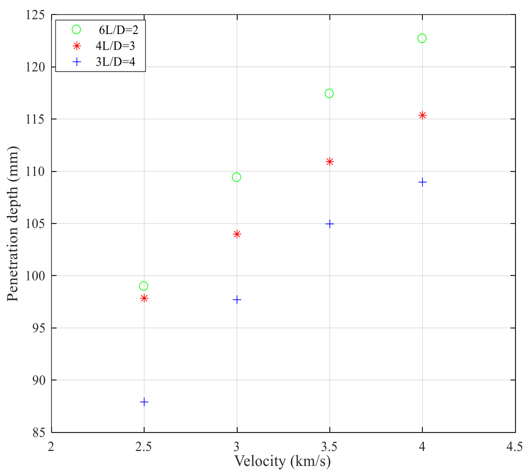

Fig. 9 The effect of L/D at $2500 \le V \le 4000\,m/s$.

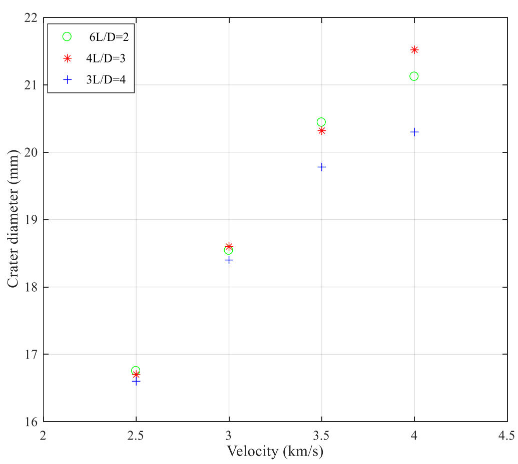

Fig. 10 The crater diameter for various L/D at $2500 \le V \le 4000\,m/s$

Finally, Figure 10 shows the crater diameter for a segmented projectile with various aspect ratios at $2500 \le V \le 4000\,m/s$. In the range of $2500 \le V \le 3250\,m/s$, the crater diameter is approximately the same for different values. However, with increasing velocity from then on, the difference in the crater diameter is observed, which is due to the formation of a larger mushrooming nose at the moment of impact in this velocity range.

5 CONCLUSIONS

In this research, SPH method has been used in Autodyn code. Its main advantage over other methods (Lagrangian and Eulerian) is the lack of meshing of the subject under analysis. Significant deformations occur at high velocities and examinations in other approaches often make further calculations impossible. Another advantage of the SPH approach is the possibility of modelling the effects of cracking, scattering of the elements formed by the impact of the projectile on the target. Due to the disadvantages of segmented projectiles with $L/D \le 1$, the simulation of segmented projectile with $L/D = 2,3,4$ is discussed. This aspect ratio range is better than projectiles with $L/D \le 1$ because it forms both the primary and secondary phase of penetration. Also, these types of projectiles (short-rod projectiles) have a higher penetration efficiency compared to projectiles with $L/D \ge 10$ (Long-rod). An increase in penetration depth of 40 to 60% has been observed in this type of projectile compared to the continuous projectiles. Also, the efficiency of this type of projectile for velocities greater than $2500\,m/s$ can be concluded. Of course, there is a lot of reversibility in the target when impacting these types of projectiles, which can be due to the momentum, high pressure and temperature that occurs in the target in high velocities. Also, at $2500 \le V \le 4000\,m/s$, the penetration depth increases at any given velocity, with increasing the number of segments, the penetration depth increases. The crater diameter also increases relatively with increasing velocity in this range.

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