Research of the projectile's layout for penetration capability through metal targets

M Yu Orlov, V P Glazyrin and Yu N Orlov
National Research Tomsk State University, 36 Lenin Avenue, 634050, Tomsk, Russia

Abstract. Present paper deals with research of behaviour metal targets impacted by ogive-nosed and blunt-nosed projectiles at 290 m/s. A complex continuum mechanics model was used to describe the material behavior under impact. Numerical modeling of perforation of metal plates with projectile are performed using IMPACT computer code. As test problem, single-plate ballistics test was modeled. In order to verify the model and method, the ballistic experiment was simulated. Good agreement with experimental data was obtained. The results of numerical simulation are shown as computed "Projectile - target" configurations, time dependences of the residual projectile velocity and the computed values of the residual velocity. It has been found that by changing the projectile layout it is possible to increase the residual velocity up to 80%. The deformation mechanisms of targets resulting from different noses shapes of projectile were also studied.

1. Introduction

The processes occurring in solids under shock and explosive loading are the subject of systematic research by various scientific groups world over. This is due to the breadth of the use of scientific results in various spheres of human life. In the works [1-5], only traditional applications are considered, including new protective structure and means of their destruction, hydro-stamping, shock-wave pressing, explosive hardening, safety of nuclear reactors, etc. It should be noted that the accumulated experience in the field of solids mechanics and fracture of materials is of interest in astrophysics and medicine.

It is obvious that the most important task is to improve the impact resistance of protective structure, including light weight ones and the penetration capability of projectiles. The problem is by no means easy. As part of this complex problem, it is necessary to create a low-noise or silent weapon for anti-
terrorist activities. Silent weapons or ones with a low initial velocity are also in demand where the use of more powerful weapons is situationally acceptable, for example, on board an aircraft during flight.

Armour-Piercing (AP) projectiles constitute a major issue when designing military armours for personal and vehicle protection. The bullet’s core, made of tungsten or strong steel alloy, defines the penetration capability of the projectile so its characterisation is crucial for both understanding failure modes occurring in the core and performing a numerical simulation of impact [6]. Numerical modeling is a convenient theoretical tool that makes it possible, without large material costs, to identify the main mechanisms and regularity of the process of destruction of bodies, including the determination of the highest penetrating capability of projectile and ballistic limit. It has been said more than once that the ability to have information about the stress-strain and thermodynamic state of materials under load is one of the main advantages of numerical simulation [7].

In work [8] impact behaviour UHSC-targets against the ogive-nosed projectile penetration at impact velocities between 540 m/s and 810 m/s was investigated numerically study using LS-DYNA. In [9] ballistic performance of monolithic, double- and triple-layered metallic plates impacted by a 7.62-mm APM2 projectile in the velocity range of 775-950 m/s was investigated. It was found that monolithic plates have a better ballistic performance than that of multi-layered plates made of the same material. This is a matter which is also raised in [10]. There was proved that monolithic metal targets impacted by compact impactors in the range up to 1500 m/s have a higher impact resistance than two-layer targets under equal conditions. In work [11] ballistic performance of multi-metal targets, including single metal multi layer systems was studied. In [12] the experimental and numerical results identified three defeating mechanisms effective on perforated armor plates which are the asymmetric forces deviates the 7.62 mm armor piercing projectile from its incident trajectory, the bullet core fracture and the bullet core nose erosion. Experimental results, including deformation of target and residual velocity after perforation aluminium plates (1 mm) by ogive-nosed projectile formed the basis of a subsequent finite element analysis of the problem using the ABAQUS 6.3 code [13].

Based on the foregoing, it follows that the search for the optimal structural layout of the projectile one of the ways to increase the projectile penetration capability. In current paper, the penetration of metal plates with projectiles was studied in subsonic velocity range. The present paper will mainly describe and discuss the ballistics performance metal target impacted 9-mm-projectiles at 290 m/s by using lagrangian numerical method, which combined with experimental results. The paper is structured as follows: phenomenological model of material behavior and numerical method, including single-plate ballistic test are stated in section 2; The numerical simulation behavior of metal plates impacted by 9-mm-projectile presented in section 3; Section 4 analyzed ballistics performance metal plates, including experimental data. Section 5 presented the conclusions derived from the results of the study.

2. Model and method

The section focuses on the phenomenological model of interacting bodies under loading and the numerical modeling method. The phenomenological model was outlined earlier in [14] and is therefore briefly outlined below. The numerical method is based on the lagrangian approach to describing the motion of continuous media and is a development ones from [15]. To simulate the problems of penetration and perforation, special algorithms have been specially developed and improved, including the algorithm of splitting nodes.

From the point of view of this model, material is modeled by a porous, compressible, elastic-plastic medium without phase transitions with averaged physical and mechanical property from [2]. The governing equations are based on the fundamental laws of conservation of mass, momentum and energy. A complex model of continuum mechanics to describe the material behavior under dynamic load is used. To describe the shear strength of a body, the Prandtl – Reuss constitutive equations and the von Mises yield condition were used [16]. In the process of material destruction under dynamic loading, new free surfaces, including fragmentary destruction are allowed. When modeling
fragmentary fracture, the concept of joint formation of shear fractures and tear-off fractures is implemented to the mathematical model.

The system of equations is solved in the two-dimensional axisymmetric statement on the basis of the Lagrangian approach to the description of the motion of continuous media. Well-known fact is that any lagrangian method has serious problems with modelling tasks of the deep penetration of projectiles into multilayer targets. For example, one is the penetrating of multi-layer targets by ogive-nosed projectile. The problem is the overlap of the triangulated elements [17]. To overcome this lack, the algorithm erosion of elements, algorithm of splitting nodes, the algorithm for constructing the free surface were introduced.

In order to verify the adequacy of the phenomenological model, the numerical method, as well as all algorithms, internal, qualitative and quantitative tests were carried out. The calculated results were compared with the experimental data and the data obtained analytically using the Rankine – Hugoniot conditions. The discrepancy with the analytical solution was 2%, with experimental data no more than 10%.

2.1 Test computations

Figure 1 shows a comparison of the computed results and experimental data for single plate ballistics test. In [18] the ballistics test are provided and use bullet 57-H-181 as projectile and 0.8mm-steel-plate as target. Initial velocity is 315 m/s. The projectile is made of a copper jacket inside which a lead filler without strong hard steel core.

According to Selivanov’s terminology, such a test is called a quantitative test. In this case, the subject of comparison is the projectile residual velocity, as well as the morphology of destruction of bodies, including the residual deflection and deformation targets, shortening of the projectile, the diameter of the hole, etc.

For test there is reasonable agreement between computed and experimental results. For example, the diameter of the inlet hole was almost identical to the original diameter of the projectile in its cylindrical part. The projectile itself practically did not deform plastically. The plate material was pulled out in the axial direction. A "plug" was cut from the plate after the one was perforated. There were very few fragments of steel plate.

![Figure 1. Comparison of the computed results (right) and experimental results (left) for single-plate ballistics test. Time moment is 40 μs. Left photo made by T. Fazylov.](image)

It was found that after perforating the plate, the computed residual projectile velocity was 284 m/s.

Experimental and numerical results are compared and a good agreement between the two has been found. The discrepancy with the experimental data was approximately 8%.

3. Ballistic performance of metallic plates impacted by a projectiles

The results of numerical simulation of perforation of metal targets, including the "projectile – target" configuration, graphical dependences of the relative projectile velocity versus time are given below. The time of perforation of the targets, the diameter of the hole in those, the time of initiation of the first foci of destruction in the materials, and the residual displacement of the targets were computed numerically. In this research, the ballistic limit was not considered as research subject. In the
following three subsections presents simulation results perforating aluminum, steel and titanium plates. Numerical modeling was performed using the IMPACT 2D computer code [19].

3.1 Projectiles and targets

In total, four types of ogive-nosed projectiles, including ones with flat of head are considered. Structurally, the projectiles are bodies of rotation and consist of three elements: a steel shell, a lead jacket, and steel core. The diameters and masses of all component parts of the projectiles are equal. The outer diameter of the shell is 9.25 mm, thickness is 0.5 mm, weight is 3.53 g. Shell material is “mild” steel. The core diameter is 7.4 mm. Jacket weight is 1.6 g. The projectiles total mass is 15 g. Core material are U10A steel, 10 Steel, lead, tungsten alloy (VNZh, Tungsten – Nickel – Iron), Uranium and gold. In the current article, the last four materials have not been considered. Targets material are aluminum alloy D16, Steel 3, high-strength steel (HSS), titanium. Projectile velocity is 290 m/s.

Figure 2 shows the cross-section of the projectiles. Here 1 is “Shell”, 2 is “Core”, 3 is the “Jacket”. Projectile with ogive-nosed are designated as $B_1$, $B_2$, $B_3$, $B_4$ projectile has flat of head part. $B_3$ projectile is semi-sheathed, and the $B_3$ projectile is ogive-nosed with a flat core.

![Figure 2. Projectile’s cross section. The projectiles are numbered from left to right. 1 – Shell, 2 – Steel core, 3 – Brass Jacket](image)

The physical and mechanical parameters of the materials are shown in Table 1. The last three characteristics relate to the criteria of failure materials.

| Parameters | Metal and alloys |
|------------|------------------|
| Parameter name | Aluminum alloy D16 | Titanium | Lead | Steel 3 |
| $K_1$, GPa | 76.5 | 116.2 | 41.7 | 153 |
| $K_2$, GPa | 267.4 | 116.8 | 115.9 | 176 |
| $K_3$, GPa | 42.8 | 124.6 | 101 | 53.23 |
| $\rho_0$, g/cm$^3$ | 2.78 | 4.45 | 11.34 | 7.84 |
| $C_0$, km/s | 5240 | 5110 | 2160 | 4417 |
| $G$, GPa | 25.8 | 39.2 | 5.6 | 81.4 |
| $\sigma_f$, GPa | 0.274 | 0.92 | 0.02 | 0.42 |
| $\sigma_k$, GPa | 0.8 | 2 | 0.03 | 2.8 |
| $A_p$, Joule$10^3$/kg | 35 | 55 | 80 | 45 |
| $\varepsilon$, Equivalent plastic deformation | 1.2 | 1.5 | 2 | 1.3 |

$\varepsilon$ is dimensionless.
3.2 Aluminium target impacted by projectiles $B_1$-$B_4$

This subsection presents the results of modelling the perforation of 4 mm and 8 mm aluminium targets. First, consider the results of simulation perforating 4-mm aluminum plate with an initial velocity of 290 m/s. The first foci of destruction formed in aluminum after 3 μs of perforation in all case. This was accompanied by the compaction of the material and its deformation in the axial direction.

The “Projectile – target” configurations at times 40 and 80 μs are shown in figure 3. The figure represents that there were different mechanisms for perforating plates. So, the projectiles $B_1$ and $B_2$ seemed to pierce the targets. As they penetrate, they move apart and compact the material of the plates around the head part and at the same time displace the material first to the front side and then to the back side of the plate. Projectiles $B_3$ and $B_4$ perforate the target, cutting off the plug in it, which is formed due to shear stresses that are beyond the limit for a given material, arising along the diameter of the blunt head part. In all four cases, the shell and jacket are removed from the core and remain on the face of the plate. Wherever the plug is sheared off, it moves at a faster velocity than the projectile, so the distance between the projectile and the plug increases over time. The shape and residual dimensions of the shell, core and holes obtained in computations and experiments correspond to each other [20].

![Figure 3. 4-mm-aluminum plate impacted by projectiles. The impact was left to right. Cross-section of projectiles $B_1$ and $B_4$. Top row – projectile $B_4$, bottom row - projectile $B_4$. The time is 40 and 80 μs.](image)

Figure 3 shows a graphical plot of the relative velocity of the projectile versus time. The relative velocity of the projectile was calculated as the ratio of the residual velocity to the initial velocity. The figure shows the perforation time and the time of numerical simulation of each case separately. The maximum perforation time was 165 μs and recorded for the $B_1$ projectile, and the minimum time was 42 μs and recorded for the $B_4$ projectile. The velocity curves had sections of rapid decrease in velocity and sections of its slow decrease. Moreover, the sections of rapid decrease in velocity were at the beginning of the perforation process.
Next, we analyze simulation results perforating 8-mm-aluminum plate. The final stage of the process of interaction of projectiles with an 8-mm-aluminum plate is shown in figure 4. We see that the perforating process 8-mm-aluminum plate was similar perforating 4-mm-aluminum plate. Projectiles $B_1$ and $B_2$ pierce the plate, and projectile $B_3$, $B_4$ cut off the “plug” in it. The figure 5 shows that the shell bounces off the face of the plate due to the elastic reaction of the material.

![Diagram](image1)

**Figure 4.** Relative projectile velocity versus Perforation time.

![Diagram](image2)

**Figure 5.** Final cross sectional configurations “Projectile – 8-mm-aluminum target” and Relative projectile velocity versus Perforation time.

Time for projectiles $B_1$, $B_2$, $B_3$ and $B_4$ was 410, 270, 505, and 225 μs, respectively.
Thus, in this subsection, the main mechanisms of interaction of $B_1$-$B_4$ projectile with aluminum plates had identified numerically. In both cases, those plates had perforated with projectiles $B_1$ and $B_4$ through. The velocity curves were very similar to each other.

### 3.3 Mild steel targets impacted by projectiles $B_1$-$B_4$

The next research objects were a 4-mm-steel and 8-mm-steel plates. Plate’s material is low alloy Steel.3. Thus, the thickness of the first plate was half that of the second. As in the previous subsection, the simulation results will help to reveal the influence of the plate thickness on the residual projectile velocity. Obviously, in the first case, the projectile velocity will be higher. But, steel is a stronger material than aluminum.

In figure 5 illustrates the final configurations "Projectile – 4-mm-steel plate" (see top row). The mechanism for breaking through plate in this case remains the same, i.e. projectile $B_1$ and $B_2$ pierce the plate, and projectile $B_3$ and $B_4$ cut “the plug”. The ogive-nosed projectiles $B_1$ and $B_2$ were not plastically deformed. The hole diameter in target practically coincides with the original diameter of the projectile. On the bottom row of the figure can be seen final configurations "Projectile – 8-mm-steel plate". In this case, none of the projectiles perforates the plate, but it should be noted that projectile with a classical ogive-nosed, unlike blunt ones, penetrate the plate much deeper. After the impact the $B_4$-projectile on 8-mm-plate, maximum its residual displacement in the axial direction took place.
Figure 6. Cross-section of configuration “Projectile – 4-mm-steel plate” (top row) and ones for “Projectile – 8-mm-steel plate” (low row) at different time.

Figure 7 illustrates the graphs of the dependences of the relative residual velocity versus perforation time. The curves are shown for the case with through penetration and for the case without through penetration. It can be seen that the curves begin to diverge almost immediately at the beginning of the process.

Figure 7. Relative velocity for projectile $B_1$ versus Perforation Time
Upper curve for 4-mm-steel plate, bottom curve for 8-mm-steel plate.

The curves for other cases were similar. Moreover, for the case without through penetration, the rest of the velocity curves were located below.
3.4 4-mm-metal target impacted by projectiles $B_1$-$B_4$

In this subsection, the research objects were titanium and steel plates of the equal thickness. The thickness of plate is 4 mm. Unlike the previous subsection, we used high-strength steel (hereinafter HSS), which is a popular choice for protective structure.

![Graph](image)

**Figure 8.** Relative projectile velocity versus Perforation time for steel and titanium plate.

A detailed analysis of the "Projectile - Target" configurations for a high-strength steel target showed that projectiles $B_1$ and $B_2$ perforates the plate at the ballistic limit. The velocity of projectile $B_1$ at 220 $\mu$s of the process is 17 m/s, and the velocity of projectile $B_2$ is 19 m/s at 630 $\mu$s. This means that after few microseconds, the projectiles will either get stuck in the hole or come out of it at an insignificant velocity. It should be noted that the deflection of the steel plates in the axial direction after interaction with projectiles $B_3$ and $B_4$ was the maximum of the previously considered cases.

After the through penetration of the 4-mm-titanium plate, all projectiles have a good reserve of residual velocity. The pattern of the perforation process and the relative values of the residual velocity in the last versions of the calculations are the same as in the previous sections.

Plotted on figure 8 are the relative velocity curves versus time. There is time interval that the curves coincide in the first microseconds. In this case, the time during which the curves coincide was located in the interval below ballistic limit.

4. Results and discussion

Table 2 shows the computed results all numerical experiment. Included in Table 2 are test data from [20, 21]. From this it can be seen that projectile $B_4$ has the highest penetration capability for all metal plates, and $B_1$ has the lowest. The explanation for this, from the point of view of established concepts, an unexpected result is the difference in the mechanism of perforation of plates. In the case projectile of $B_1$, the perforation of the plates occurs as a puncture, and in the case of $B_4$, as a plug cut, which consumes less energy. As for the comparison of the computed results for the case with the $B_1$ and $B_2$ projectiles, as well as $B_3$ and $B_4$, which are similar to each other in the type of plates penetration, the difference between them is explained by the effect of the shell.
Table 2 – Computed and experimental residual velocities of projectiles

| Targets | Initial projectile velocity, 290 m/s | Residual velocity, m/s |
|---------|--------------------------------------|------------------------|
|         | D16 (4 mm)          | D16 (8 mm)          | Steel.3 (4 mm)         | HSS (4 mm) | Titanium (4 mm) |
| B1      | Computed results    | 196                 | 98                    | 167        | 17*        | 115        |
| Test data |                   | 190                 | 95                    | 166        | -          | ---        |
| B2      | Computed results    | 232                 | 131                   | 182        | 19*        | 148        |
| Test data |                   | 241                 | 135                   | 186        | -          | ---        |
| B3      | Computed results    | 240                 | 90                    | 149        | 128        | 138        |
| Test data |                   | 216                 | 87                    | 147        | ---        | ---        |
| B4      | Computed results    | 253                 | 169                   | 182        | 161        | 216        |
| Test data |                   | 258                 | 173                   | 188        | ---        | ---        |

The values of the residual velocity marked with * were for cases when there was no penetration. In these cases, the interaction process lasted 220 μs and 630 μs, respectively.

In the case of B₂, the absence of a shell on a part revived reduces its cross section, as well as the necessary energy consumption for its deformation and destruction, as in the case of B₁. There are similar reasons for the lower penetration capacity of B₃ as compared to B₄, i.e. the core in B₁ spends the initial energy additionally on deformation and destruction of the shell. In addition, part of the destroyed shell in the case of B₃ forms an attached mass to the plug, increasing its inertia.

As a result of numerical simulation, some features and patterns of deformation and destruction of the projectile and targets were revealed. On the curves of the projectile velocity, the sections of its fast and slow decrease are marked. Sections of rapid velocity decrease have always been at the beginning of the process. All targets had a residual axial displacement after projectile impact. The diameter of hole in the targets after the through penetration was approximately equal to the initial projectile diameter. The nose of the projectile had a slight erosion when the targets were pierced through. This was observed for the cases with projectiles B₁ and B₂. The diameter of the knocked-out "plug" from the targets was approximately equal to the original projectile diameter. This was observed for the cases with projectiles B₃ and B₄. In all cases, including through penetration and non-through penetration, the shell was separated from the projectile core.

5. Conclusion

Based on the research, the major conclusion can be drawn is as follows. We will answer the question posed at the beginning of the article about the possibility of the impact of the layout of the projectile on its penetration capability. Of great importance in this case is the starting shape of projectile, including its head part. Based on the numerical modeling conducted above, it can be argued that if we take B₃ as the basic projectile, then, by changing its layout, it is possible to increase the residual velocity after penetrating 4-mm-steel plate by 13%, by 4-mm-duralumin plate by 35%, and by 8-mm-duralumin plate by 80%. On the other hand, if the core of the projectile B₄ is taken as the basic case of the core, then its penetration capability can be reduced by combining it with the ogive shell of the projectile B₁.

Acknowledgments

The reported study was funded by RFBR according to the research project № 19-08-01152.
Appendices

UHSC - ultra-high strength concrete, research object from [8]
VNZh (Tungsten-Nickel-Iron alloy) - Tungsten alloy according to the Russian nomenclature of structural materials
D16 – Aluminium alloy according to the Russian nomenclature of structural materials
HSS - high-strength steel alloys
AP - Armour-piercing projectile

References

[1] Fomin V M et al 1999 Vysokoskorostnoye vzaimodeystviye tel (Publishing House of the Siberian Branch of the RAS, Novosibirsk) p 600 (in Russ)
[2] Gerasimov A V et al 2007 Teoreticheskiye i eksperimental'nyye issledovaniya vysokoskorostnogo vzaimodeystviya tel (Tomsk State University Press, Tomsk), p 572 (in Russ)
[3] Selivanov V et al 2008 Means of destruction and ammunition (Bauman Moscow Technical University Publishing House) p (in Russ.)
[4] Paul Hazell Armour. Materials, Theory and Design (CRC Press, 2016)
[5] Ben Dor G Dubinsky A and Evperin T 2019 Engineering Models In High-speed Penetration Mechanics And Their Applications (World Scientific Publishing Company, Singapore)
[6] Duplan Y, Saletti D and Forquin P (2019) Light Weight Armour Group for Defense and Security (Roubaix, France), pp 190-200
[7] Glazyrin V and Orlov Yu 2015 Numerical modelling penetration metal target with elongated combined rods XI All-Russian congress on fundamental problems of theoretical and applied mechanics (Kazan, Russia) pp 945-947
[8] Ruizhe Shao Chengqing Wu, Yu Su, Zhongxian Liu Jian Liu, Shenchun Xu 2019 Composite Structures, doi: https://doi.org/10.1016/j.compstruct.2019.04.004
[9] Flores-Johnson E Saleh M Edwards L 2011 Impact Engineering J 38 pp 1022-1032
[10] Glazyrin V and Orlov M Yu 2003 Computational technologies 8(4) pp 143-151
[11] Stewart M and Netherton M 2020 Statistical variability and fragility assessment of ballistic perforation of steel plates for 7.62 mm AP ammunition Defence Technology 16 pp 503-513
[12] Namik Kılıç, Said Bedir Atil Erdik Bülent Ekic Alper Tasdemirci, Mustafa Güden 2014 Materials and Design 63 pp 427-438
[13] Iqbal M Gupta N Sekhon G 2006 Behaviour of thin aluminium plates subjected to impact by ogive-nosed projectiles Defence Science Journal 56(5) pp 841-852
[14] M Yu Orlov et al 2020 J. Phys.: Conf. Ser. 1459 01200
[15] Holmquist T and Johnson G 2011 A Computational constitutive model for glass subjected to large strains, high strain rates and high pressures Journal of Applied Mechanics 78 051003-1
[16] High-Velocity Impact Phenomena 1970 Ed by Ray Kinslow (Academic, New York) p 579
[17] Flis W J 1987 Int. J. of Impact Engng. 5, 1-4 pp 269-275
[18] Fazylov T 2020 Numerical modelling of response multilayered metal plates impacted by 57-H-181 bullet Proc. Int. 9nd Conf. (Tomsk, Russia) pp 111-114
[19] Orlov Yu Glazyrin V and Orlov M Yu Certificate of registration computer program 2010610911 (October 2010)
[20] Glazyrin V Orlov M Orlov Yu and Frolov Yu 2007 Physics 50(9/2) pp 73-79
[21] Kanel G I (2015) Shock Waves in Relaxing Condensed Media. In: Bonazza R., Ranjan D. (eds) 29th International Symposium on Shock Waves 1. ISSW 2013. Springer, Cham. https://doi.org/10.1007/978-3-319-16835-7_8