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# EXPERIMENTAL INVESTIGATION ON THE PERFORATION OF HIGH-HARDNESS STEEL PLATE BY AN API PROJECTILE

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***Abstract:*** *In the present study, penetration of a 6 mm thick ARMOX 500T high-hardness steel plate by a 7.62x39 mm armor-piercing incendiary bullet with a hard steel core was experimentally investigated. Projectile's impact velocity has been varied in order to determine its influence on the interaction between the penetrator and the target during the penetration process. The initial velocity was measured by the optical measurement system while the residual velocity was measured using the contact screens. Analytical model for the impact velocity calculation was experimentally verified. Based on the obtained ballistic test results, ballistic limit velocity of the target plate was determined and the residual versus impact velocity curve was formed. Furthermore, categorization of the performed firings was conducted in accordance with the observed penetration process outcomes. Finally, target material failure mechanism and its change due to the increase in the projectile's impact velocity was investigated.*

***Keywords:*** *terminal ballistics, experimental investigation, penetration mechanics, armor-piercing, high-hardness armor*

## 1. INTRODUCTION

Small-arms armor-piercing incendiary (API) ammunition is designed for both the perforation of light-armored targets and the ignition of the inflammable materials. Most commonly, it comprises a hard core made from tungsten alloy or alloyed steel which serves as a kinetic-energy penetrator and the incendiary mixture which ignites the combustible materials located behind the armor [1]. As the high-hardness armor (HHA) steels are extensively used as lightweight armor [2], evaluation of their ballistic resistance against the API bullets is highly important.

Although the prediction of the penetration process outcome may be obtained with the use of empirical equations or analytical models, their usage is often limited and may lead to the results which greatly differ from the experimental data [3]. Due to the complexity of the observed processes and the number of influential parameters, work in the field of penetration mechanics is considered to be experimental in its nature [4]. In the present study, the experimental research was conducted with the aim to determine the influence of the projectile's impact velocity on the ballistic performance of both the ARMOX 500T HHA steel and the 7.62x39 mm API projectile. Projectile's impact velocity influence was observed as it is one of the major influential factors in the penetration of metallic materials, together with the material properties of the target and the penetrator and the impact geometry conditions [5]. In order to determine the sole influence of the impact velocity on the penetration process outcome, all the other parameters were kept constant, including the angle of incidence which was kept normal as that condition represents the worst-case scenario [6] from the point of target vulnerability.

A description of the experimental set-up, instrumentation and methods is given, together with the description of the projectile and the target properties. Analytical model for the calculation of the projectile's velocity drop was verified experimentally and utilized for the determination of the impact velocity. Evaluation of the errors which may occur during the tests was conducted. Residual versus impact velocity curve based on the modified Recht-Ipson empirical model was formed and the values of parameters were determined. Distinct penetration outcomes were identified and the representative photographs were given. Change in the failure mode of the target material with the change in the impact velocity was observed and analyzed.

# 2. EXPERIMENT

## 2.1. Target and projectile properties

The present study is based on an experimental investigation of the ARMOX 500T ballistic behavior when subjected to impact by a 7.62x39 mm armor-piercing incendiary projectile at the normal incidence angle and under the various impact velocities.

ARMOX 500T high hardness steel was chosen as a target material as it is extensively used for the combined protection from the penetration and blast effects. For the purpose of the present investigation, it was procured in the form of a 6 mm thick square-shaped plate with the edge size of 500 mm. The plates were quenched and tempered and their mechanical properties were determined by the manufacturer prior to the delivery (Table 1).

**Table 1**. Mechanical properties of the target material as per the manufacturers Inspection Certificate

| Target type | ARMOX 500T plate |
|---|---|
| Thickness | Nominal: 6 mm |
| | Measured: 6.34 – 6.38 mm |
| Density | 8 g/cm$^3$ |
| Hardness | 530 HBW |
| Yield strength $R_{P0.2}$ | 1468 MPa |
| Ultimate Tensile Strength $R_m$ | 1687 MPa |
| Elongation | $A_5$: 11% |
| | $A_{50}$: 13% |

Schematic drawing and the configuration of the 7.62x39 mm M 82 API bullet used in the ballistic tests may be seen in Fig. 1. The projectile comprises a hard steel core encased in the copper jacket with the lead-antimony filler between. The length of the core is 20.4 mm and its diameter is 6 mm.

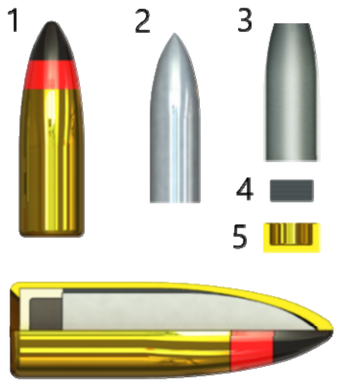

**Figure 1.** 7.62x39 mm API M 82 projectile: 1 – Jacket, 2 – Steel core, 3 – Lead-Antimony filler, 4 – Incendiary mixture, 5 – Tombac cup

The thermite incendiary mixture is inserted in a tombac cup and placed in the rear end of the projectile. Ignition of the incendiary mixture occurs upon the projectile's contact with the obstacle due to the influence of the inertial and frictional forces [1]. The mass of the projectile is 7.55 g, while the mass of the hard steel core is 3.6 g. The hardness of the steel core was measured and found to be 61 HRC.

## 2.2. Experimental set-up

Schematic representation of the experimental set-up may be seen in Fig. 2. The research was carried out by firing the 7.62x39 mm API projectiles through the ballistic test barrel into the 6 mm thick ARMOX 500T steel plate targets which were mounted in the rigid frame and placed at the distance of 25 m from the muzzle. The impact surface of the target was kept perpendicular to the projectile's trajectory throughout the experiment. A fixed boundary between the plate and the frame was achieved by the use of the clamps on the plate's corners. As stated in [6], for the high-velocity ballistic impacts in which the distance between the single shot and the plate's boundary is greater than several projectile diameters, the boundary conditions can be assumed to be of minor importance. For that reason, the distances between the adjacent shots and between the shots and the boundaries was kept equal or greater than ten projectile diameters.

The initial velocities of the projectiles have been varied in a broad range in order to determine the influence which the impact velocity has on the projectile's residual velocity and the penetration process. This was achieved by the change in the propellant charge mass. Seven velocity groups were formed starting at the 430 m/s and up to the 740 m/s with no less than five firings in each group. For the purpose of the initial velocity measurement, the infrared optical velocity measuring system was used. It comprised a chronograph and two identical IR light-barriers which were placed at the distances of 1.5 and 3.5 meters from the muzzle thus providing the V2.5. When the change in the light intensity caused by the occurrence of the projectile between the emitters and the detectors of the first barrier becomes large enough to be detected, the counter will be activated and it will be stopped only when the second barrier detects the passage of the projectile. Based upon the measured time of flight and the known value of the distance between the barriers, the initial velocity can be determined.

Ballistic properties of several intermediate cartridges including those of the 7.62x39 mm steel-cored AP projectile were investigated and the set of equations describing the projectile motion were defined [7]. Based on those equations and the measured initial velocity, the impact velocity at the distance of 25 meters can be calculated. However, additional tests were made with the aim to determine the spread in the values of impact velocities and the difference between the calculated and the measured values. Those tests were conducted without the target and with the pairs of contact screens placed both in front and behind of the holding frame. A contact screen (Fig. 3) consists of two 0.1 mm thick aluminium foils separated by a 5 mm thick cardboard layer that acted as insulator and prevented the flow of the electrical current between the foils thus keeping the circuit open. In the case of screen being penetrated by a projectile or sufficiently large fragment which can provide electrical contact between the foils, the circuit would become closed thus triggering the time counter. The front pair of contact screens (marked with 4 in Fig. 2) was used for the measurement of the impact velocity, while the rear pair (marked with 6) was used for the measurement of the velocity drop caused by the front pair of screens.

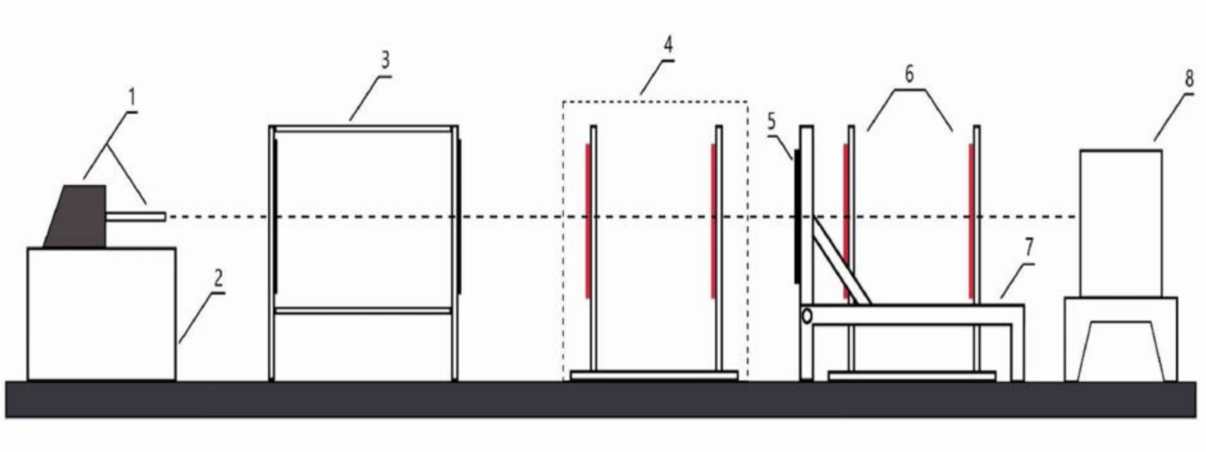

**Figure 2.** Scheme of the experimental set-up: 1 – Ballistic breech and test barrel, 2 – Universal stand, 3 – IR velocity measuring system, 4 – Contact screens for the impact velocity measurement, 5 – Target plate, 6 – Contact screens for the residual velocity measurement, 7 – Supporting frame, 8 – Catching box

Upon ending the impact velocity measurement tests, the front pair of contact screens was removed together with its supporting frame in order to evade the inducement of yaw angle and the velocity drop prior to the projectile's impact. On the other hand, the rear pair of contact screens wasn't removed and was kept operating throughout the experiment with the purpose of measuring the projectile's residual velocity. Advantage of the contact screen based velocity measuring system is that it is insensitive to the flash and light effects of the burning incendiary mixture. Those effect can cause the deterioration of the functionality when some of the other velocity measuring systems are employed, e.g. the high-speed cameras [8]. Furthermore, it is relatively inexpensive and makes it possible to trace the trajectory of the projectile after the perforation. Comparison of the residual velocities obtained by the contact screens and the acceleration data integration has shown that the measurement error when using the contact screens is minor [9].

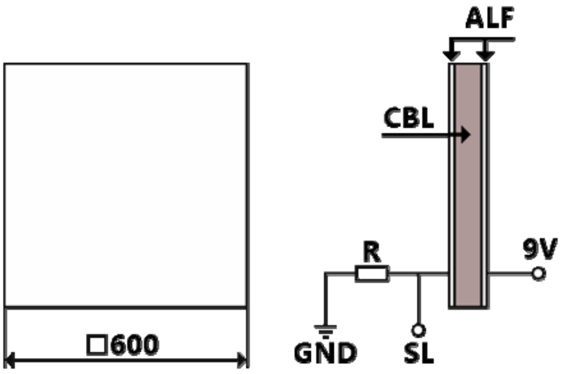

**Figure 3.** Scheme of a contact screen: ALF – Aluminum foil, CBL – Cardboard layer, SL – Signal line

A catching box filled with sand was used for the soft recovery of the penetrators and the target plate fragments. Mass and geometric properties of the collected specimens were measured in order to obtain the insight into the failure mechanisms. Furthermore, the properties of the openings in the target plate formed during the perforation process were measured and analyzed with the same goal.

The obtained experimental results and their analysis can be found in the following sections.

## 3. RESULTS

The impact velocity measurement was conducted and the results which may be seen in the Fig. 4 were acquired. In-addition, the analytical model for the calculation of the projectile's velocity change during the flight was developed and the curves were formed for the $V_{2.5}$ velocities corresponding to those measured during the tests. The value of the drag coefficient used in the model was equal to 0.343, as defined in [7] for the 7.62x39 mm AP projectile. Even though the drag coefficient changes its value with the change of the Mach number, the comparison between the measured and calculated data shows that the difference is not greater than 0.6% in any of the firings and thus, the assumption was made that the constant value of the drag coefficient may be used.

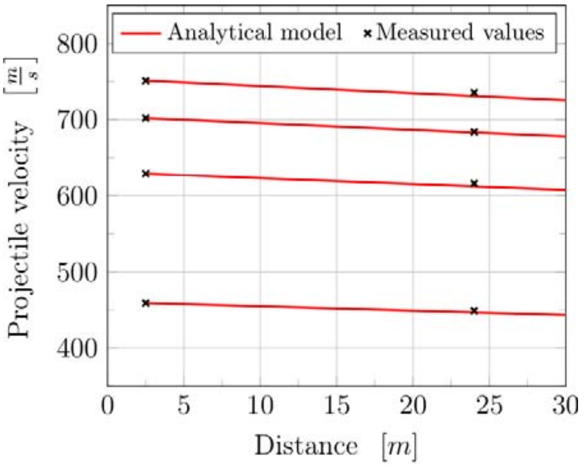

**Figure 4.** Projectile's velocity decrease – comparison between the analytical model and the measured values

The velocities obtained by the rear pair of contact screens have shown that the velocity drop caused by the passage of the projectile through the two pairs of contact screens was equal to 3.2% at most. During the residual velocity measurement tests, the front pair of contact screens was removed thus reducing the number of screens which the projectile has to penetrate and consequently, the induced velocity drop was also reduced to the value which is considered as acceptable.

Upon the verification of the developed analytical model, calculation of the impact velocity became possible.

### 3.1. Residual velocities

Seven test groups were formed with no less than five firings in each of them, with the only difference between the groups being in the values of their nominal $V_{2.5}$ velocities. The lowest velocity group had the nominal value of 430 m/s as the risk of projectile getting stuck in the barrel could arise if the lower velocities were selected. On the other hand, the highest value of initial velocity was 740 m/s as this is the standard ordnance velocity for the selected bullet type. Intermediate groups were placed at the 470, 520, 560, 600 and 680 m/s. Change in the initial velocity value has been achieved through the change in the propellant mass and even though this was done with great care, slight variation in the measured values of velocities are observed. However, this poses no threat to the objectives of the conducted research.

Results obtained during the tests may be seen in Fig. 5 where the measured residual velocities are plotted against the impact velocities. Close-up views of the target's impact and rear surfaces and two of multiple recovered penetrator fragments are also displayed. Based on the in situ analysis of the target plate and the contact screens, the firings were divided into five distinct groups. Least frequent of them comprised the only two cases in which the perforation was not achieved. Both of them occurred in the lowest initial velocity group and were beneficial for the determination of the ballistic limit velocity $V_{bl}$. As per [3], the $V_{bl}$ may be found as the average between the highest velocity not providing perforation and the lowest velocity under which the perforation of the target was achieved. In Table 2, the penetration process outcome for the first group of firings can be found. It is important to note that although the perforation was achieved in three out of five firings from the Group I, the residual velocity was not measured. During the analysis of the target plate it was discovered that the diameter of the openings created by those firings was between 4.7 and 5.1 mm which, having in mind that the diameter of the penetrator's cylindrical section is 6 mm, led to conclusion that the penetrator itself didn't pass through the target. This conclusion was verified by the finding of penetrators in the area between the barrel and the target. Although the fragments were ejected from the target plate, they were either not sufficiently big to achieve the contact between the foils or were ejected at an angle that would make them miss the contact screens thus preventing the residual velocity measurement.

**Table 2**. Ballistic test results for the Group I

| No. | Initial velocity $V_{2,5}\left[m/s\right]$ | Impact velocity $V_i\left[m/s\right]$ | Opening in the target plate |
|---|---|---|---|
| I-1 | 427.0 | 414.9 | No |
| I-2 | 433.5 | 421.3 | Yes |
| I-3 | 436.7 | 424.4 | No |
| I-4 | 437.0 | 424.7 | Yes |
| I-5 | 447.0 | 434.4 | Yes |

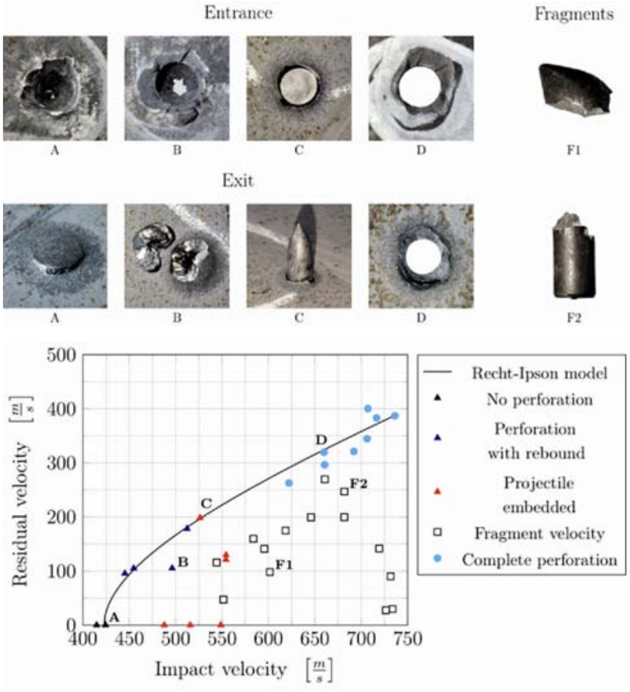

**Figure 5.** Impact and rear surfaces of several representative firings and the experimental residual versus impact velocity curve based on a best fit to the modified Recht-Ipson model

Based on the results presented in Table 2, the ballistic limit velocity has been found to be equal to $V_{bl} = 422.8\ m/s$. Relationship between the impact velocity and residual velocity can be established by using the well-known model of Recht-Ipson [10], which in the case of the perforation of a plate by a penetrating projectile has the following form:

$$V_r = (V_i^2 - V_{bl}^2)^{0.5} \qquad (1)$$

However, it was found that the Eq. 1 may not provide a perfect fit with the experimental results in a number of cases, e.g. when the projectile's deformation cannot be considered small [3], when the friction is not taken into account [11] and when the mass of the ejected target material may not be considered negligible. In order to provide a better fit with the experiment, the modification which includes the empirical coefficients may be used:

$$V_r = a\left(V_i^p - V_{bl}^p\right)^{1/p} \qquad (2)$$

where the $a$ and $p$ are fitting parameters. In Fig. 5, the curve representing the best fit of the residual versus impact velocity data and the proposed empirical model is shown. The values of fitting parameters are found to be $a = 0.68$ and $p = 1.8$. It may be seen that the curve represents the data in the lower impact velocity zone with almost no deviation, while with the increase of the impact velocity the deviation between the model and data also increases. The residual versus impact velocity curve has a relatively high gradient in the vicinity of the ballistic limit velocity which is in agreement with the experiment results, as it was seen that a small change in the impact velocity near the $V_{bl}$ may cause great variation in the value of residual velocity and the outcome of the penetration process.

In the lower range of the observed impact velocities, apart from the aforementioned group in which the perforation was not achieved, two more groups were noticed. Four firings resulted in a perforation with a projectile rebound, with the size of the created openings ranging from 1.6 mm to 5.2 mm. Residual velocities of the ejected fragments were measured for all of those cases and good match with the Recht-Ipson curve was achieved (Fig. 5). Six firings in the impact velocity range from approximately 490 m/s up to 550 m/s have resulted in the penetrator embedment in the target plate. The zone of impact velocities in which this group of firings is located partially overlaps with the zone in which the perforations with rebound are placed. Identification of the projectile sticking phenomenon indicates the significance of the friction between the penetrator and the target during the penetration process, which can amount up to three per cent of the projectile's kinetic energy loss [12]. Highest measured value of residual velocity in the group of embedded projectiles is in a close match with the residual versus impact velocity curve, while the two other measured values greatly deviate from the empirical model. In those cases, fragments from both the target plate and the penetrator were collected. As it may be seen from Fig. 5, there are two more firings nearby for which the fragment velocities were detected, but although the measured velocities are similar in value, outcome of the penetration process is different as in the two firstly described firings the penetrator was embedded while in latter two the complete perforation was achieved. Detection of this transition is significant as it indicates which value of impact velocity is sufficiently high to provide complete perforation and passage of penetrator through the target plate.

With the further increase of the projectile impact velocity, two different outcomes were observed. Penetrator achieved complete perforation either without breaking or it was fragmented during the penetration process. As shown in Fig. 5, first case of complete perforation for which no fragmentation of the penetrator was observed appeared at the impact velocity of 622 m/s, indicating that there is a zone of velocities starting at around 525 m/s with the width of 100 m/s in which all of the firings have resulted in penetrator fragmentation with residual velocities significantly lower than predicted by the empirical model. On the other hand, with the impact velocities greater than 622 m/s the penetrator had achieved the equal number of complete perforations with and without its fragmentation. Residual versus impact velocity curve had become significantly less steep in the zone of higher impact velocities as the level of kinetic energy converted to the work during the projectile/target interaction had decreased. Deviation between the experimental results and the empirical model had increased for the higher velocity impacts which can be attributed to the observed penetrator fragmentation and severe projectile deformation.

### 3.2. Failure mechanisms

Three modes of material failure known as ductile failure, adiabatic shear plugging and discing have been identified as most common in the penetration of metallic armor [5]. Due to the anisotropy of the target material and the non-ideal impact conditions, mixed modes of failure may be expected in practical cases of penetration rather than the ideal ones [4]. In the present study, influence of the impact velocity on the target plate failure mode was investigated.

In the vicinity of the ballistic limit velocity, two cases of partial shear plugging were observed where one of them is shown in Fig. 5 as A. Asymmetric bulges were formed on the rear surface with the maximum heights of 1.3 mm and 1.5 mm and diameters of 5.6 mm. On the impact surface, the indentations were formed with the penetrator-shaped cavities being 5.2 mm and 5.5 mm deep. As stated in [13], in any penetration process it is energetically favorable for the first part of penetration to be achieved through the ductile hole formation which will then be followed by the plugging mode upon sufficient reduction of the target thickness. Described behavior was observed in the aforementioned partial shear plugging cases where ductile hole enlargement preceded shear plugging. Similar behavior was seen in three other firings from the Group I in which the plug ejection was achieved and the target was perforated even though the projectile was rebounded. Several cases of rear surface bulging and brittle failure were observed during the second stage of the penetration (Fig. 5(B)) in the transition zone where the projectile embedment was seen. Still, majority of the impacts in that zone resulted in shear plugging during the second stage of penetration. For the highest values of impact velocities, ductile failure modes become predominant modes of material failure in both the initial and final stages of penetration and the plugs weren't recovered for the impact velocities greater than 690 m/s.

## 4. CONCLUSIONS

Ballistic performance of the ARMOX 500T high-hardness steel plate under the impact of 7.62x39 mm armor-piercing incendiary projectile was experimentally investigated. Impact velocity has been varied in a range from the ballistic limit velocity to the nominal projectile's velocity. Some of the important conclusions and observations are:

- Analytical model for the calculation of impact velocity has been verified experimentally. Deviation between the model and the test results has been found to be sufficiently small on the observed range of velocities,
- Experimental set-up and utilized instruments were able to provide the initial and residual velocity data
- Empirical model of Recht-Ipson can provide accurate prediction of the residual velocity, especially in the lower range of the observed impact velocities, although the deviations have increased with the occurrence of penetrator fragmentation,
- Impact velocity increase results in reduction of the slope of the residual versus impact velocity curve. Also, it results in the increased chance for the penetrator fragmentation,
- Transition zone with the high probability of penetrator embedment in target plate was observed indicating the zone in which the friction and elastic recovery of the target material have great influence on the penetration
- Relatively wide zone of intermediate impact velocities was observed for which the target perforation is accompanied with the penetrator fragmentation. This has led to the decrease in residual velocity which indicates that additional effort needs to be put with the aim to improve penetrator's mechanical properties.

Future work will be focused on the utilization of the acquired experimental data in the development of the numerical model for the observed penetration process.

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