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Influence of Add-On Perforated Plates on the Protective Performance of Light-Weight Armour Systems

Teresa FRAS*, Norbert FADERL

French-German Research Institute of Saint-Louis (ISL),
5 Général Cassagnou Str., 68301 Saint-Louis, France
**Corresponding author's e-mail address: teresa.fras@isl.eu*

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Abstract. The presented experimental investigation, aimed at verification of defeat mechanisms against small-calibre projectiles, provided by 4-mm-thick perforated plates with different material- and geometrical properties, was performed. A regular pattern of punched holes in steel plates increases the possibility of asymmetrical contact between the plate and projectiles which may cause threat destabilization, rotation or fragmentation depending on the impact position. Three tested armour configurations comprise the super-bainitic high-hardness Pavise™ SBS 600P armour steel plates perforated by elongated holes of size 4 × 12 mm (the first configuration), the martensitic high-hardness Mars® 300P steel plates perforated by circular holes with a diameter of 5 mm (in the second configuration); and in the third configuration, the martensitic Mars® 300 plates perforated by oblong holes (4 × 10 mm) were used. The performed impact tests proved that the tested add-on plates assured high protection against the impact of 7.62 × 51 .308 Win P80 hard-core armour piercing (AP) projectiles. It was also observed that the plates caused similar mechanisms of bullet failure.
Keywords: mechanics, perforated add-on armour, armour-piercing (AP) projectile

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1. INTRODUCTION

One of possible improvements in passive protection of armoured vehicles against small-calibre projectiles are add-on armours. Perforated add-on armours, adjusted in front of the main-armour, destabilize a threat and reduce its penetration capability before it reaches the main armour. A high perforation percentage of the pre-armour plate does not cause a high weight increase. The hole pattern in such plates increases the probability of asymmetrical contact between the projectile and the plate ([1-4]), due to which small-calibre projectiles may be destabilized or fragmented before reaching the main-armour. It is experimentally observed that depending on the hit-point with respect to neighbouring holes, different mechanisms can cause projectile failure. The core of the armour-piercing projectiles could be shattered, fragmented, partially eroded or rotated, [1-4]. The contact asymmetry is strongest when a projectile impacts a hole edge, leading to bending the projectile core and to its subsequent failure. The design of perforated pre-armour plates has been a subject of various studies, patents, and publications, e.g. [5]. [2] presents an analysis of impacts of 7.62, 12.7, and 14.5 B32 API projectiles in 4 and 5-mm thick plates made of bainitic steel Nano-Ba perforated by circular holes; in addition, plates were inclined at several angles during the ballistic impact tests. Experimental results confirm that angles of impact highly influence the behaviour of API projectiles. The API projectiles of small- and medium-calibre are still effective penetrators during impact at small angles $\alpha < 20°$ (from the normal to the surface of the armour). When the angle of impact increases, the B32 API projectiles are susceptible to shattering. The most intensive shattering was observed during perforation at the angle $\alpha = 0°$, when the cores shattered into many small fragments.

Different steel manufacturers propose diverse materials of various properties and thicknesses, perforated in different hole patterns and sizes. The holes may have various cross-section shapes (such as circular, oval, triangular or square, [6-8]) but to be efficient, they must correspond to the threat diameter – which is the biggest drawback of such a protective system. In general, the hole size should be smaller than a threat diameter but still large enough to influence the projectile, [8].

The distance between the holes should be smaller than the width of their cross-section area, as it was found that then the probability of projectile encountering the slot increases [8]. Researches and optimisations of geometrical and material properties of the perforated plates are still a current challenge, e.g [10-11].

The objective of this study is to analyze defeat mechanisms against small-calibre projectiles provided by perforated plates which have different material properties and perforation patterns.

4-mm-thick high-hardness Pavise™ SBS 600P bainitic steel plates slotted with elongated holes, were used in the first tested configuration.

The martensitic high-hardness Mars® 300P steel plates perforated by circular holes, were used as the pre-armour in the second one and the same steel but perforated by elongated holes was tested as a third armour solution. In the tested configurations, perforated plates were adjusted 200 mm in front of 8-mm-thick Mars® 190 plates. The thickness of perforated plates and size of holes make them suitable against impacts of armour-piercing projectiles of the calibre 7.62 × 51 .308 Win P80. A number of shots in different points was performed to analyse influence of the properties of the tested perforated plates on the bullets behaviour.

2. TESTED ADD-ON PERFORATED PLATES

The ultra high-hardness perforated armour steel Pavise™ SBS 600P belongs to a group of so-called 'super-bainitic' steels, [12-13]. The bainitic structure is considered to be very hard but also brittle and prone to cracking. The super-bainitic structure is refined and enhanced, so the final material is strong and the density of interfaces is higher than in other metals of this type, [14]. After the heat-treatment and introduction of additions, the material gains ultra-high strength without the brittle nature of bainite. The nano-bainitic steel has an ultimate tensile strength of 2500 MPa, a hardness of 600-670 HV and toughness in excess of 30-40 $MPam^{1/2}$, [15]. Super-bainitic steel cannot be welded without losing its unique characteristics, which limits its applications. When bainitic steels are applied as add-on passive armour, they may be attached to the main armour with screws.

The hole pattern of the tested bainitic perforated plate is given in Fig. 1. Each hole has a size of 4 x 12 mm and ligaments between them (vertical and horizontal) have a width of 5 mm. According to the manufacturer, the areal density of such a plate is equal to 22.3 kg/m^2.

Mars® 300 is an ultra high-hardness armour steel used also for add-on armour applications. It is characterized by the minimum yield strength of 1300 MPa and a minimum hardness of 580 HB 40, [16]. Mars® 300 should not be heated above 130°C in order to maintain the guaranteed hardness. As representatives of this steel grade, 4 mm thick plates with two different perforation patterns have been chosen. Circular holes of 5-mm diameter were the first tested pattern. Their periodicity can be described by an equilateral triangle with the vertices in the centres of three nearest holes and the side dimension of 8 mm. The second perforation configuration contains elongated holes (4 x 10 mm) with 5 mm ligaments between holes (both in the vertical and horizontal directions). The areal density is equal to 20.5 kg/m^2 and 23 kg/m^2, measured respectively for plates with the oblong and circular perforation pattern.

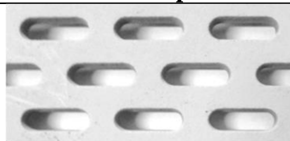
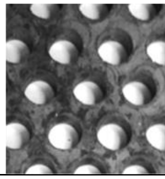
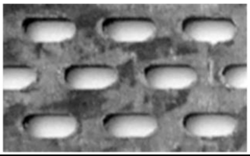
Material	Some characteristics	Perforation pattern
Bainitic steel Pavise™ 600P	*t* = 4 mm elongated holes: *d* = 4 mm,*l* = 12 mm ligaments: 5 mm areal density = 22.3 kg/m^2	
Mars® 300P	*t* = 4 mm circular holes: φ = 5 mm areal density = 23 kg/m^2	
Mars® 300P	*t* = 4 mm elongated holes: *d* = 4 mm, *l* = 10 mm ligaments: 5 mm areal density = 20.5 kg/m^2	

Fig. 1. Details of the perforation patterns in the tested plates

The results of quasi-static compression (for bainitic steel) and tension (for martensitic steel) are presented in Fig. 2.

(a) (b)

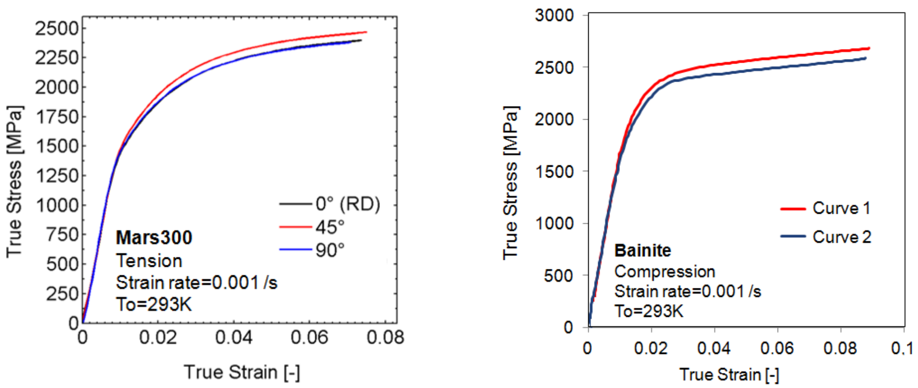


Fig. 2. Curves resulting from quasi-static tests:
a) compression for the martensitic Mars® 300, [11], and b) tension for the bainitic Pavise™ 600P steel

The steels available for the authors (a rod of the bainitic steel and the Mars® 300 steel in sheets) did not allow performing comparative material tests. Nevertheless, the presented results show general characteristics of the steels. The yield strength in compression for the Pavise™ 600P steel is close to 1800 MPa, whereas its plastic strength is close to 2400 MPa.

The yield strength in tension for Mars® 300 is equal to 1400 MPa and the plastic strength reaches 2250 MPa. As it is guaranteed by their producers, both steels are characterized by high strength and relatively (regarding the values of strength) high ductility.

Plates of the given geometrical properties are supposed to provide protection against 7.62 × 51 AP P80 projectiles, Table 1. In the standardized procedure of evaluating a protection level of logistic- and light-armoured vehicles VPAM [17], these threats shot from a distance of 10 m at the impact velocity close to 820 +/- 10 m/s cannot perforate the tested armour (to fulfil requirements of level 9 of VPAM).

In the specification of the Mars® 190 steel (a reference rolled homogenous armour (RHA) steel), [19], it is stated that plates with a thickness of 16.5 mm assure protection against 7.62 × 51 hard-core armour piercing (AP) projectiles – the areal mass of such a plate is 129.7 kg/m^2. Application of a 4-mm thick perforated plate caused the reduction of the main-armour weight to 8 mm. The areal mass of the total armour (4-mm thick perforated plate, 200-mm air gap, 8-mm thick main armour) is equal to 85.2 kg/m^2 (with a perforated bainitic plate), 86 kg/m^2 (with a martensitic plate perforated by circular holes) and 83.4 kg/m^2 (with a martensitic plate perforated by oblong holes).

Table 1. 7.62 x 51 FMJ/PB/HC (.308 Win.) AP bullet, [18-19].

Cartridge designation	7.62 x 51 AP P80 (.308 Win)	
Case type	rimless, bottleneck Full Metal Jacket	
Bullet diameter	7.82 mm	
Neck diameter	8.8 mm	
Shoulder diameter	11.5 mm	
Base diameter	11.9 mm	
Rim diameter	12 mm	
Case length	51.2 mm	
Overall length	69.9 mm	
Cartridge weight	25.4 g	
Bullet weight	10 g	
Muzzle energy	3304 J	

Destabilization of projectiles after passing though, the first plate increases due to the air gap between the pre-armour and the main armour, since the projectile deflection increases with the distance. In practical applications, the gap between the plates is much smaller to reduce the overall thickness of the armour. However, in the performed experiment, such a distance made observations of the projectile behaviour after the perforation of the first plate possible, which was necessary to analyse the influence of perforated plates on the bullet behaviour.

3. PERFORMED BALLISTIC IMPACT TEST

During the experiment, the tested plates of a size 250 × 250 mm were mounted in a stiff frame and located in the catch-box, Fig. 3(a). Each target was subjected to four shots. The shots were recorded by a high-speed camera and by a fast flash X-radiography, Fig. 3(b).

The exact impact point was recorded for each shot by an ultra-high speed camera Shimadzu HPV1 with a resolution of 312 × 260 pixels, an exposure time 125 ns and a frame rate of 1 million fps.

Due to the distance between the plates, the application of a triple-time flash X-ray device was possible. The projectile behaviour was observed in three time steps. The first X-ray image was taken just before the impact; the second and the third captured the position of the projectile 50 and 130 mm behind the first plate. Pictures were made in two planes showing the side and the bottom view of the projectile at flight. To verify repeatability of the obtained results, for each configuration at least 8 shots were performed.

During the experiment, single impacts were shot from the gun. After each one, a plate position was changed so that another impact reached an undamaged zone. In a real battle situation, multi-hits could be expected. If several projectiles hit the same place in the perforated plate, it loses its protective properties.

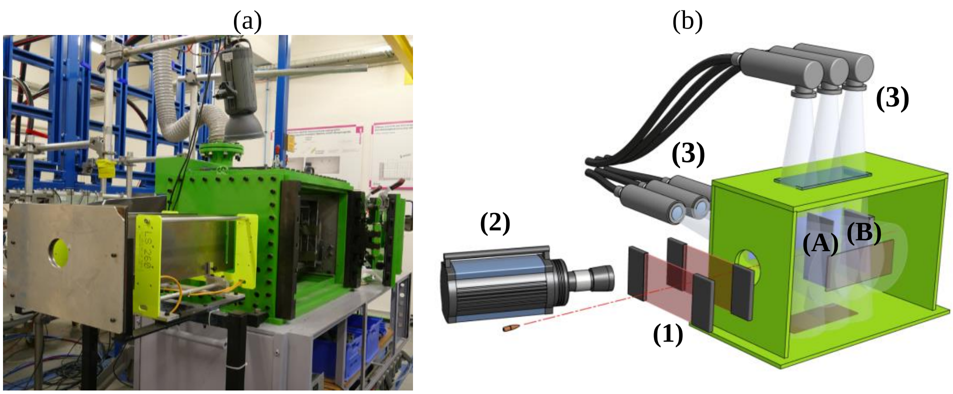
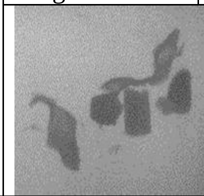
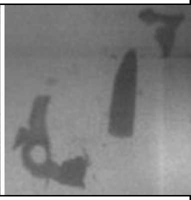
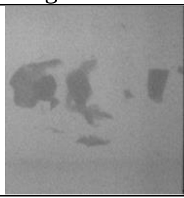
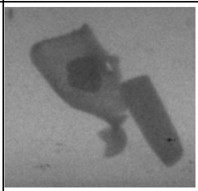
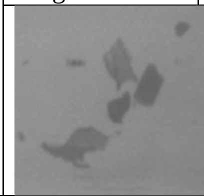
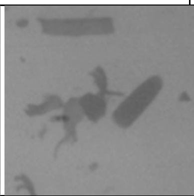
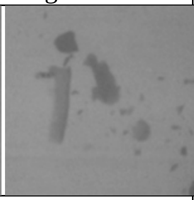
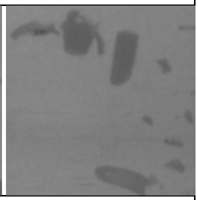
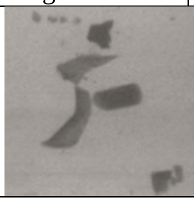
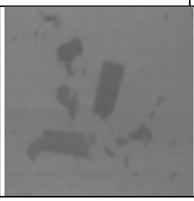
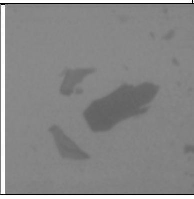
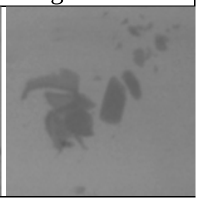


Fig. 3. Experimental set-up (a), and its schema (b): (A) perforated plate, (B) Mars® 190, (1) dual-light barrier, (2) ultra-high speed camera, (3) triple flash X-radiography

The tested projectiles of the given calibre, 7.62 × 51 AP P80 (.308 Win), behaved similarly after the contact with the plates, perforated by various hole patterns. In all impact cases, projectiles did not perforate the main-armour plate. The observed behaviour of the projectiles may be categorized in three general groups according to a hit point and the resulting failure.

Table 2. Projectiles 130 mm behind the perforated plate on the flash-X ray images.

Pavise 600TM steel	Core fragmentation	Deviation	Core fragmentation	Nose erosion + deviation
				
Mars® 300 steel, circular holes	Core fragmentation	Nose erosion + deviation	Core fragmentation	Nose erosion + deviation
				
Mars® 300 steel, elongated holes	Core fragmentation	Nose erosion + deviation	Nose erosion + deviation	Core fragmentation
				

Depending on the hit position, an AP .308 Win projectile may be strongly deviated, if it hit in a hole, it may be broken into pieces if it hits a hole-edge and if it hits the area between holes, the core tip erodes and the remaining part of the core deviates from its initial trajectory. The projectile was considered to be fragmented if its core was broken into two pieces visible on the flash X-ray picture. Shattering of the projectile cores in small pieces (observed in impacts of 7.62 API Dragunov projectiles, [2]) did not occurred for this less powerful calibre of AP projectiles. Some results, captured by the flash X-ray radiography at 130 mm behind the first plate are summarized in Table 2.

The impact velocity V_0 of the projectile was measured by a light barrier just before impact. The flash X-ray images were used to determine the projectile residual velocity.

Figure 4 presents a comparison of the measured velocity decreases after impacts. In the case of the bainitic plates, the average drop of velocity for impacts in hole-edges and between holes was calculated as 9% and 10%, whereas for the impacts inside a hole, the velocity drop was found to be 14%. More scattered values of the core velocity were measured for the impacts in the martensitic steel plates.

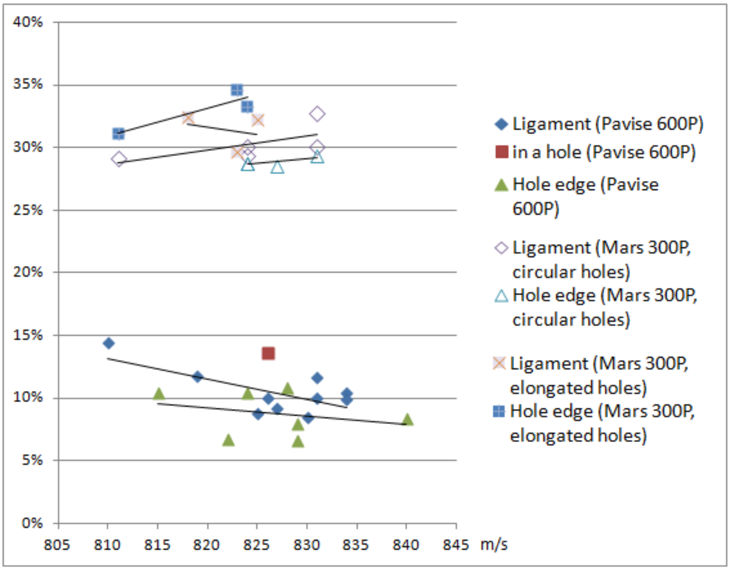


Fig. 4. Decrease in the bullets impact velocity

Among all impact cases, the hit inside a hole was the rarest. For 24 shots in the bainitic perforated plates, only one shot hit in a hole. The martensitic plates were impacted 8 to 10 times, none of impacts occurred to hit in a hole.

For plates which were perforated with both circular and elongated holes, the drops of velocity were higher than those measured for impacts in the bainitic plates. The perforation pattern with circular holes caused the velocity decrease close to 30%, whereas plates perforated by elongated holes caused slightly higher velocity decreases, in average close to 35%. Without an accurate characterization of plasticity and fracture properties, it is difficult to explain the reasons of this difference in the plate performance.

4. IMPACT POSITIONS AND PROJECTILE BEHAVIOUR

The position of the projectile in the moment of impact affects its failure. The performed test was registered by the high-speed camera, which recorded the moment of the impact and additionally, by the flash X-ray radiography documenting the bullet behaviour after passing through the plate. Comparison between the observation provided by these two different techniques allows coupling the hit point with the resulting bullet failure. Three representative examples of defeat mechanisms provided by the tested steel plates against AP .308 Win are described below.

- **Projectile hits inside a hole**

Impacts in a hole should be considered as the most dangerous cases for the armour. In Figs. 5-6, it may be seen that the bullet tip passed through a hole without damages but the periphery of the projectile touched the inner edges of the hole, which caused peeling of the brass jacket off and deflecting the core from its initial trajectory. The core remained undamaged and continued its flight but its destabilisation increased with the distance, which weakened its perforation capability.

Figure 5 presents a range of damages which were limited by the edges of the nearby holes – four holes were affected. Some parts of the rear plate side were pushed back, Fig. 5(b). The mass loss resulting from this impact was found to be 6.6 g.

The trace of the core is clearly seen in the main-armour and it indicates that in the impact moment the core was almost parallel to the plate which caused reduced damages to the plate

(a)

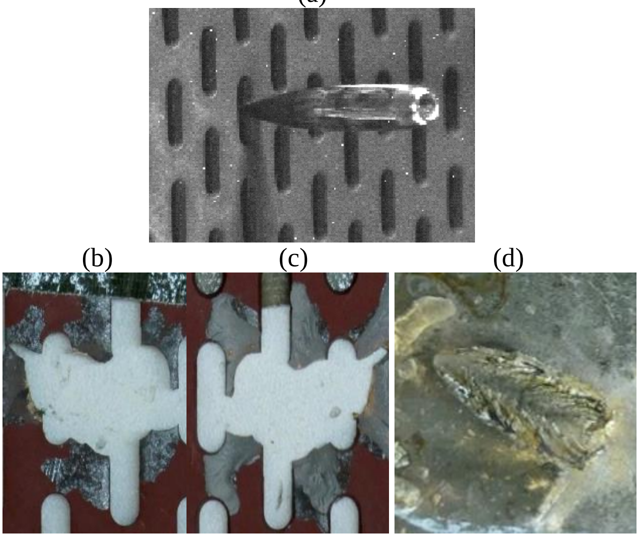


Fig. 5. Projectile hit in a hole of the bainitic perforated plate: a) impact position. Damage mode of the pre-armour plate: (b) front face, (c) rear face and (d) deformation of the main armour

The undamaged core tip is clearly seen on the X-ray images, Fig. 6. Based on the images, the spatial angle of the core was found to be equal to 83° after 130 mm of the flight. The main-armour plate was only slightly damaged due to the impact, Fig. 5(d). The initial impact velocity of the bullet was measured to be 826 m/s and the core residual velocity was reduced to 714 m/s after 130 mm of the flight.

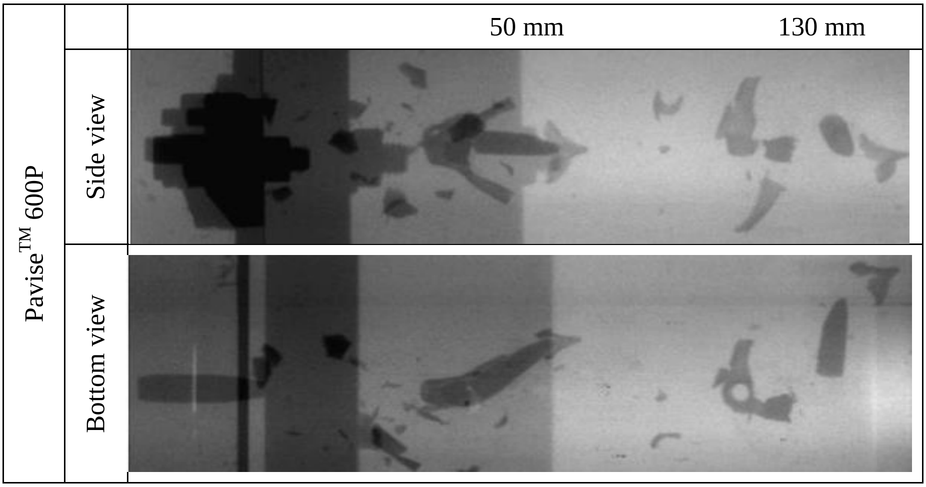


Fig. 6. Flash X-ray images of the trajectory of the bullet which hit in the hole center

- **Projectile hits in a ligament between holes**

The second kind of mechanisms leading to the bullet failure was observed when projectiles hit the area between holes. Hitting in a ligament between holes caused an erosion of the projectile tip and a deviation from the initial trajectory. Impacts in ligaments occurred in 60% of all performed shots in three tested configurations.

Figure 7 presents the flash X-ray images of the impacts in ligaments between holes of three tested perforated armour plates. It was observed that due to such impact positions, the brass jacket was partly peeled off, the projectile was not broken but a part of its mass was eroded due to the contact with the plate.

Damage of the plates due to these impacts is presented in Fig. 8. The damaged area is limited to the holes surrounding the impacted position. In most of cases of plates with elongated holes, only 4 holes were affected. Depths of penetration measured in the main armours were smaller than 1mm.

The rotation of the core was increasing with the distance and was more distinct after 130 mm of its flight. For the bainitic plate, the core deflection from the initial trajectory was measured as 23°, 25° and 32°, respectively in the planes XZ and YZ and as the resulting spatial angle. The bullet velocity decreased from 825 m/s to 753 m/s. The example of the ligament impact in the martensitic plate perforated by circular holes, shows that the core was almost parallel to the main armour after 130 mm of the flight (the spatial angle close to 80°).

The core tip erosion and the increasing rotation of its remaining part significantly reduced the penetration capability of the bullet. The core velocity dropped from 811 m/s to 575 m/s.

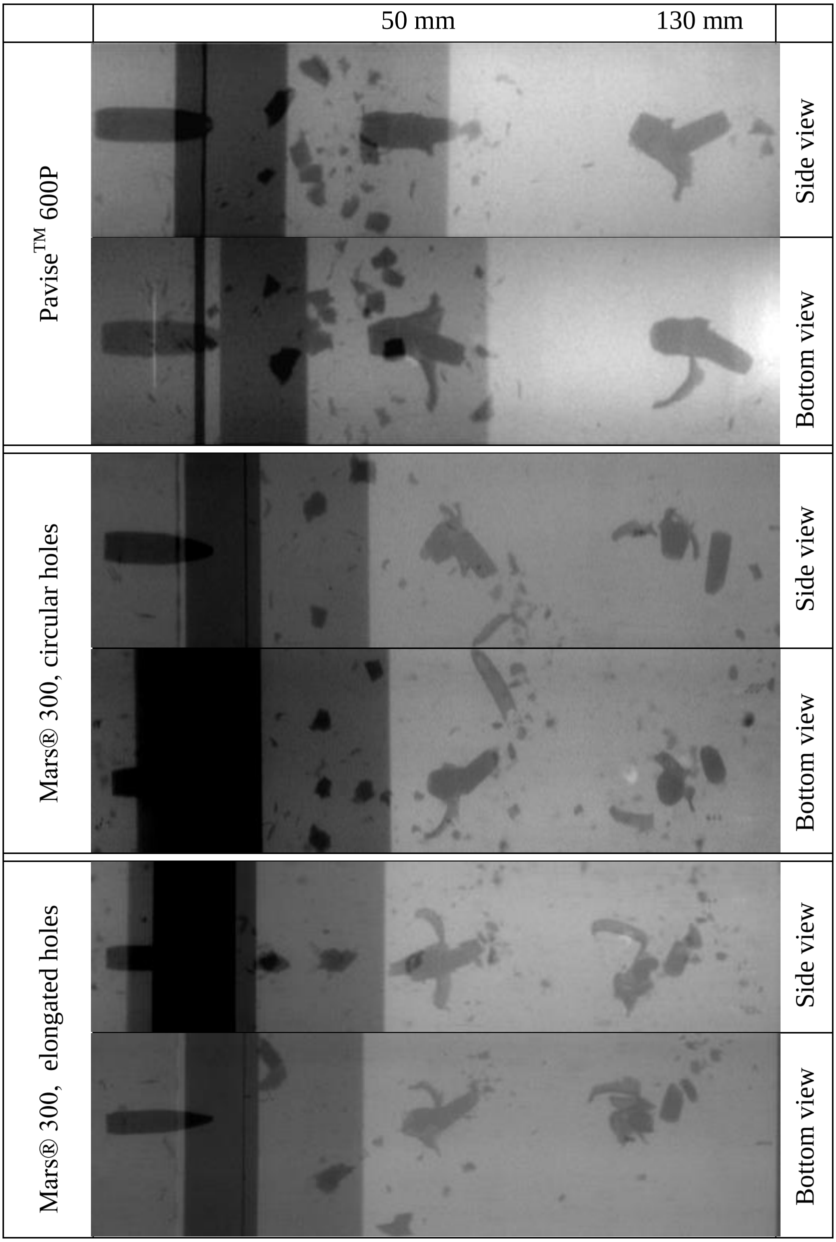


Fig. 7. Flash X-ray images of the projectiles which hit in the ligaments between the holes

The Mars® 300P plate with slotted holes caused also a strong deviation of the projectile core. After 130 mm of the core flight, the angles of core deviation were close to 110° and 17° measured in the planes XZ and YZ, which resulted in the spatial angle close to 75°. In this case, the projectile velocity dropped from 819 m/s to 550 m/s

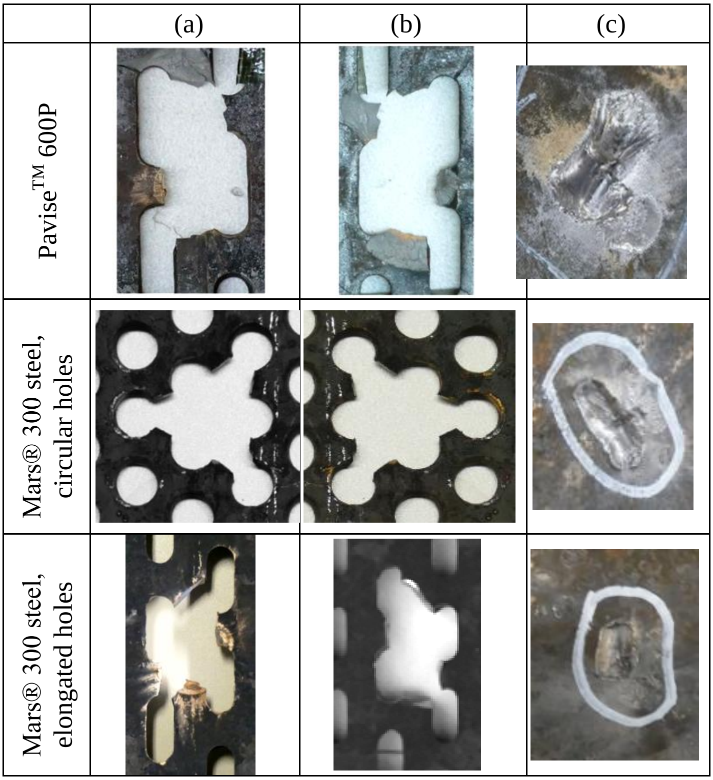


Fig.8. Damage modes resulting from the impacts in ligaments. Perforated plates: (a) front face and (b) rear face. (c) Damage of the main armour

The last observed kind of the projectile failure occurred when a projectile hit a hole-edge. In all tested perforation patterns, this impact position caused the breakage of the bullet core.

- **Projectile hits a hole edge**

The asymmetrical contact between the bullet and a plate led the projectile to deviate from the inclination direction. While passing through the hole, the tip of the projectile was going up, whereas its rear part remained in the previous position – consequently, the core undergoes bending, [3].

Since the core steel is of a high hardness and low ductility, the induced tensile stress caused the core fracture. The breakage of core was observed in the tests of the perforated armour plates, Fig. 9.

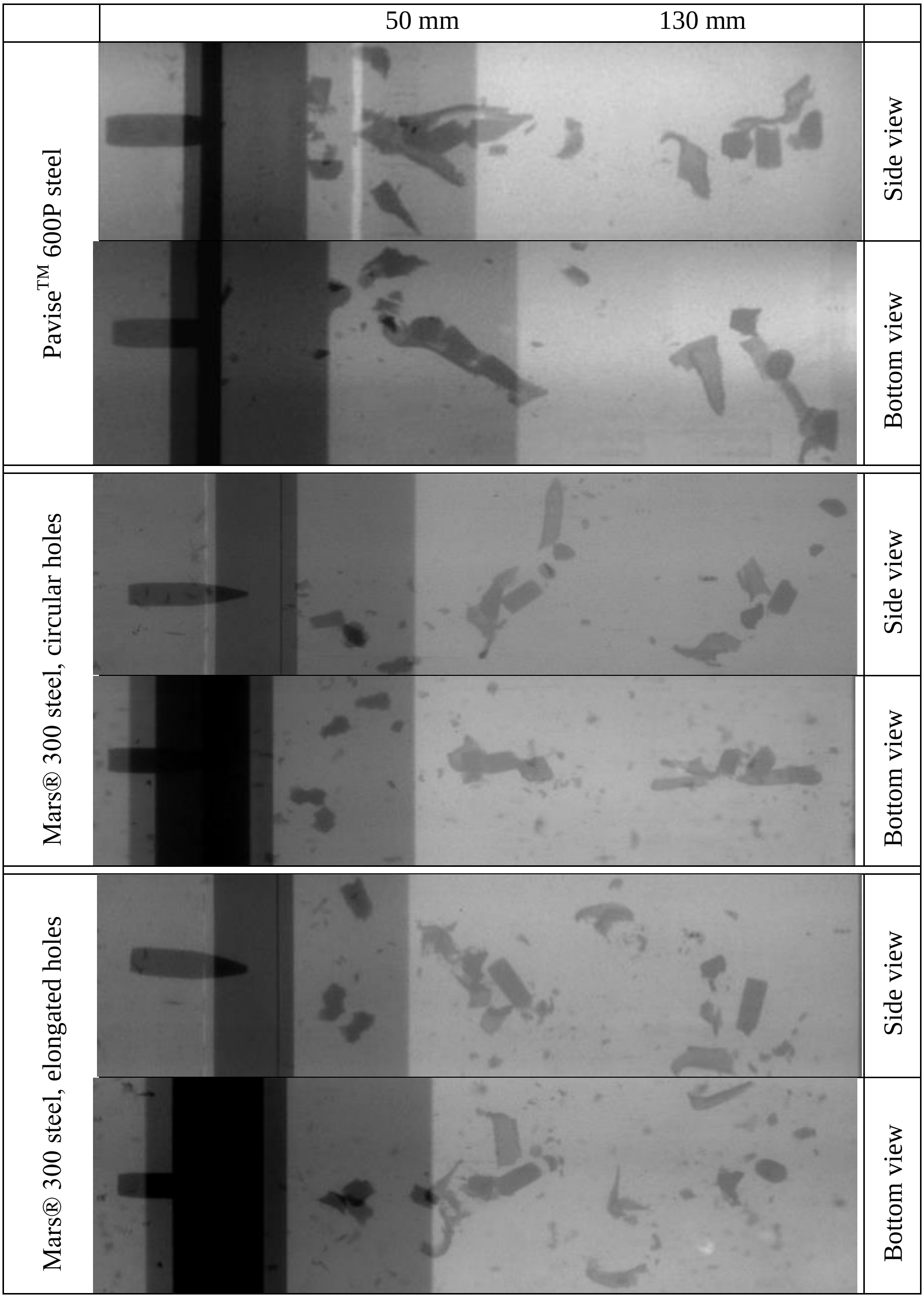


Fig. 9. Flash X-ray images of the projectiles which hit a hole edge

Impacts in hole-edges caused the most efficient reduction of the projectile perforation capacity, since the projectile is fragmented just after passing through the plate. The distance between the strike face and the main armour is of minor importance, since the core is defragmented just after passing through the strike-face plate. Core pieces hit the main armour with the decreased velocity, causing no serious damage, Fig. 10(c).

Within the recorded impacts in one plate geometry, a different number of holes were affected; damaged ranges of the perforated plates had different extents. In Fig. 10, the exemplary pictures of the resulted damages are collected. In [11], a study on different impact locations in Mars® 300 was carried out showing that even a slight change of the hit position results in a different damage range, which confirms the sensitivity of fracture of such steel plates to the bullet point of impact.

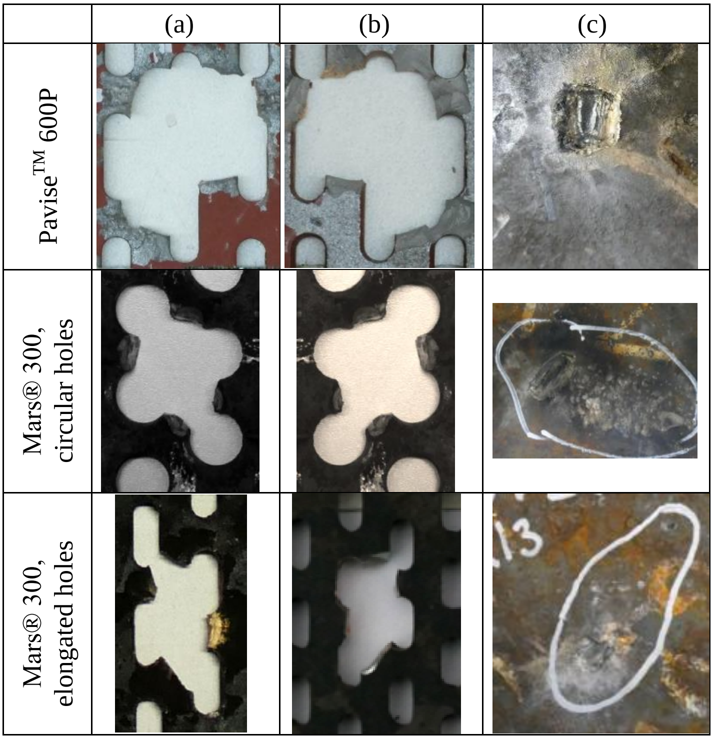


Fig. 10. Damage modes resulted from the impacts at a hole-edge. Perforated plates: (a) front and (b) rear face. (c) Damage of the main armour

5. CONCLUSIONS

The discussed experimental investigation was performed to verify the efficiency in the reduction of the small-calibre perforation capacity, provided by perforated armour plates with different material and geometrical characteristics.

As add-on armours, the bainitic steel Pavise™ SBS 600P perforated by elongated holes (4 × 12 mm) and martensitic Mars® 300 steel perforated by circular (diameter 5 mm) and by elongated holes (4 × 10 mm) were used. Plates of these perforation patterns and thickness of 4 mm are proposed as shields against 7.62 × 51 .308 Win P80 AP projectiles. In the experimental configuration, the perforated plate was attached 200 mm in front of the 8-mm thick main armour. Due to this distance, a flash X-ray device was enabled to follow a trajectory of disturbed projectiles. The areal mass of the tested armours, 83 – 86 kg/m^2, is significantly smaller than the areal mass of a 16.5 mm thick Mars®190 plate (129.7 kg/m^2), considered to be a reference homogenous armour.

For three tested armour concepts, similar mechanisms of defeating 7.61 AP projectiles were observed, depending on the impact position. Basing on the experimental observations, the projectile behaviours may be categorized in three groups. A bullet of the given calibre may be strongly deviated from its initial trajectory (when hits in a hole); may break into pieces (if hits a hole-edge) or it may be partially eroded and rotated (due to impacts in a ligament). When a projectile hits a hole-edge, the asymmetry of contact is the strongest – the core undergoes bending and because it is made of steel with a high hardness and low ductility, it tends to fracture. In this impact case, the distance between plates is of a minor importance, consequently this is the most efficient way of reducing capacity of small-calibre, hard-core projectiles.

It was observed also that the martensitic steel plates caused an average 30% velocity decrease, which was independent from the perforation pattern. The bainitic steels reduced the projectile velocity by a14%. It may be concluded that material properties play an important role in the performance of perforated plates.

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