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IS A HARD TOP LAYER ALWAYS THE RIGHT CHOICE?

M.J. van de Voorde[1], K. Herlaar[2], J.P.F. Broos[3]

[1] *TNO Defence, Security and Safety, Lange Kleiweg 137, P.O. Box 45,*
2280 AA Rijswijk, The Netherlands, martin.vandevoorde@tno.nl
[2] *koen.herlaar@tno.nl*
[3] *hans.broos@tno.nl*

Operational requirements for vehicles result in a constant trade-off between protection and mobility. Mobility limits the weight of the armoured vehicle despite the fact that it needs protection against several threats. In metallic armour systems the hardest material is normally used at the outside of the vehicle. This paper shows that in some situations it is beneficial to use the harder material at the inside of an armour system. Experiments are done with three types of ammunition from level 1 and 2 of the STANAG 4569 on several metallic armour systems of steel and aluminium. Furthermore, numerical simulations are performed to help understand the phenomena involved in these impact situations. The stripping of the jacket off the projectile core seems to be an important aspect when an armour system is designed out of two different materials. It can be beneficial to place the ‘soft’ material in front of the ‘hard’ material.

INTRODUCTION

While operating in countries like Afghanistan and Iraq, army personnel more frequently encounters more severe threats than ever. These situations require armouring of their vehicles, like jeeps and trucks. Operational requirements for vehicles result in a constant trade-off between protection and mobility. Mobility limits the weight of the armoured vehicle despite the fact that it needs protection against several threats.

Designing an armoured vehicle, one would normally use the guideline of using the hardest material at the outside of the vehicle. This paper will show that in some situations it is beneficial to use the harder material at the inside of an armour system. In this way, an armour system can be designed with a lower surface weight and therefore weight reduction can be obtained.

Experiments with metallic armour systems were performed with small calibre ammunition. Experiments will be shown with three different types: 7.62x39 mm

Kalashnikov API BZ, 5.56x45 mm Ball (M193) and 5.56x45 mm ‘AP’ (SS109). These three types are chosen since protection against this ammunition is required for level 1 and 2 of the STANAG 4569, protection levels of logistic and light armoured vehicles [1]. Furthermore, explicit numerical simulations will be shown which are helpful in understanding the phenomena involved in these impact situations.

RESULTS FROM BALLISTIC EXPERIMENTS

The ballistic experiments are performed at the Laboratory for Ballistics Research in Ypenburg (The Hague, The Netherlands) of TNO. The impact velocity is measured by the use of IR light screens. The residual velocity is measured by the analysis of the photographs made by the Ultra High Speed IMACON camera at the back surface of the target. Therefore, the uncertainty in the measurement of the residual velocity is approximately 5 %. The IMACON camera is triggered by the last IR light screen at 38 cm before the target. The trigger delay necessary to photograph the residual projectile is recalculated for each projectile-target-velocity combination.

Table 1 shows the test matrix of armour systems tested against different projectiles with their corresponding impact velocities. In this matrix the different metallic armour systems are listed with their corresponding surface weight (kg/m^2). An *x* in Table 1 indicates that this combination is not tested.

Table 1. Matrix showing which metallic armour systems are tested against which projectiles and corresponding impact velocities (*x* indicates that this combination has not been tested)

Metallic Armour System	Surface Weight (kg/m^2)	7.62x39 API-BZ	5.56 SS109	5.56 M193
3.2 mm Mars 240	25	*x*	~ 900 m/s	~ 937 m/s
10 mm Al7020	28	~ 695 m/s	~ 900 m/s	~ 937 m/s
6.4 mm Mars 240*	50	*x*	~ 900 m/s	~ 937 m/s
6.4 mm Mars 240* + 18 mm air +10 mm Al7020	78	~ 695 m/s	*x*	*x*
10 mm Al7020 + 18 mm air + 6.4 mm Mars 240*	78	~ 695 m/s	~ 900 m/s	*x*
10 mm Al7020 + 6.4 mm Mars 240*	78	~ 695 m/s	*x*	*x*

* 6.4 mm Mars 240 is actually assembled from two plates of 3.2 mm Mars 240.
The changes in the performance of the armour system caused by this assembly are neglected.

Figure 1 shows the average results of a limited amount of ballistic experiments defined as the ballistic performance. The three different colours represent the three different projectiles. Each category shows one armour system. The bars with the diagonal pattern are not the results from experiments. These bars are based upon ballistic knowledge and engineering judgement. The surface weight of the armour system increases from left to right. The ballistic performance is defined as

$$\text{Ballistic Performance} = \left(1 - \frac{V_{residual}}{V_{impact}}\right)\cdot 100\% \qquad (1)$$

with $V_{residual}$ and V_{impact} representing the residual velocity and the impact velocity of the projectile.

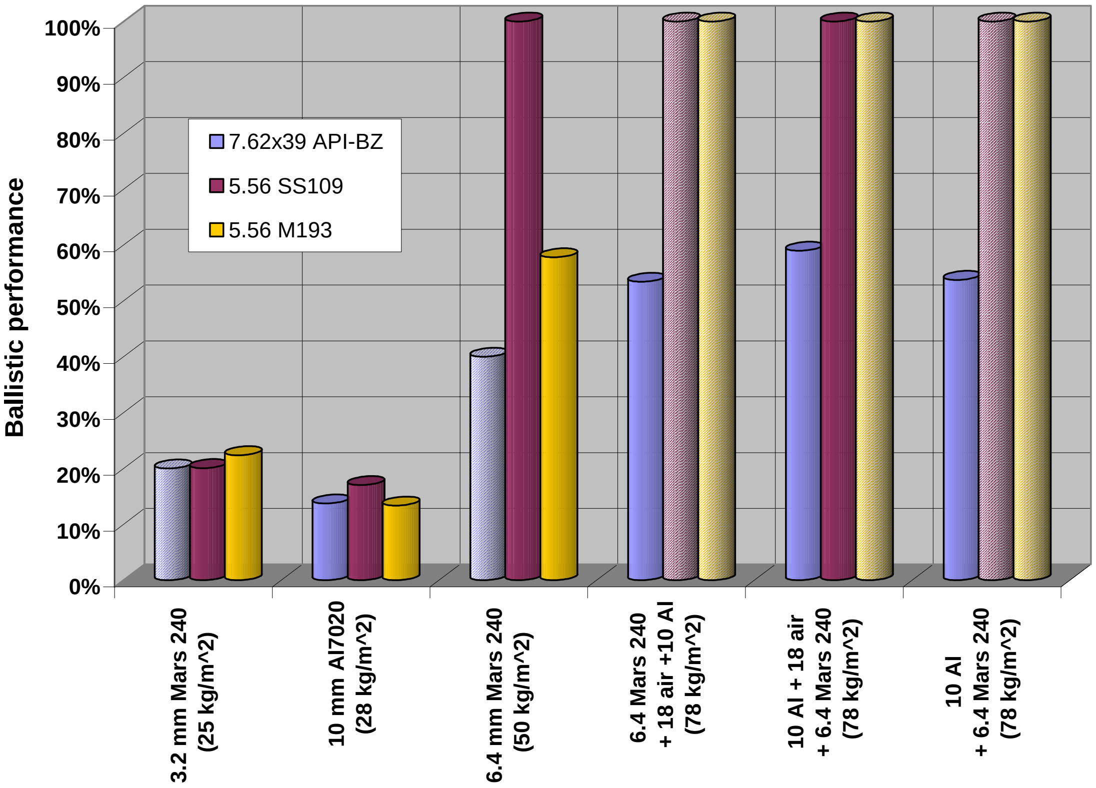

Figure 1. The average results from the ballistic experiments for the three projectiles, indicated by the three different colours. Each category shows one armour system. The surface weight of the armour system increases from left to right. The ballistic performance is defined in eq. (1).

Figure 1 shows that, as expected, the 7.62x39 API-BZ (level 2, STANAG 4569) is the heaviest threat of the three projectiles. With this projectile however, it is interesting to see that there is a trend visible showing shows better ballistic performance of the Al/steel armour system (~10 % relatively) than of the Steel/Al armour systems. In other words the ballistic performance is better when the aluminium plate is in front of the steel plate. However, this trend is based upon a limited number of experiments. In the discussion a possible explanation will be given for this trend.

Typical remains found after a shot with the 7.62x39 API-BZ are shown in Figure 2. This figure is valid for both the aluminium target and the steel target as well as a combination of both targets. It shows that the core of the projectile is not affected by the targets.

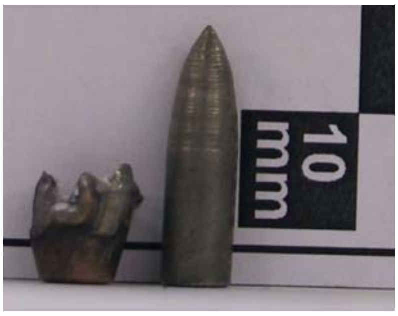

Figure 2. Remains of the 7.62x39 API-BZ.
From left to right: back-end of projectile and projectile core.

The back-end of the projectile can be found, because this back-end is ‘blown off’ by the incendiary, which is present in the back-end of the projectile. This happens after the perforation of the target. This effect is visualised in Figure 3. This figure shows a sequence of IMACON photographs during the impact of a 7.62x39 API-BZ into 6.4 mm Mars 240 + 18 mm air + 10 mm aluminium.

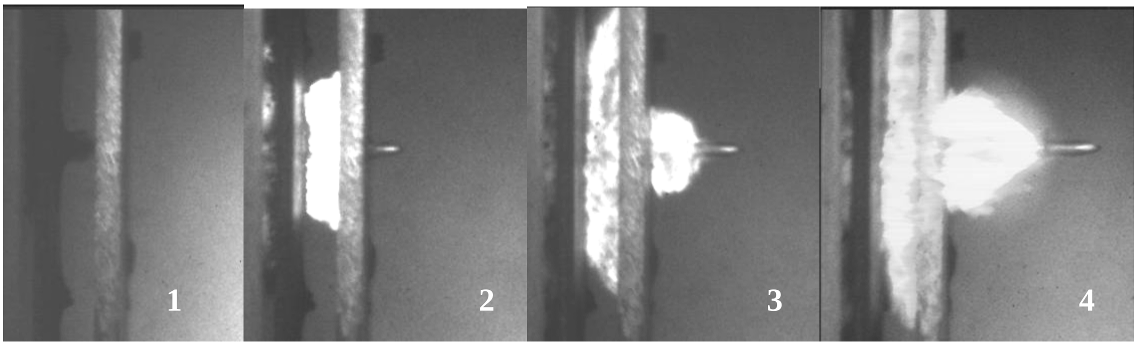

Figure 3. 7.62x39 API-BZ vs. 6.4 mm Mars + 18 mm air + 10 mm Aluminium.

Another noticeable result which can be seen in Figure 1 is that the 5.56 M193 Ball projectile can be a heavier threat than the 5.56 SS109 'AP' projectile. The SS109 is stopped by 6.4 mm of Mars 240 while the M193 Ball projectile perforates the target. Figure 4 shows a perforation in 3.2 mm Mars 240 in a sequence of IMACON photographs. This sequence is comparable to a perforation in 6.4 mm Mars 240.

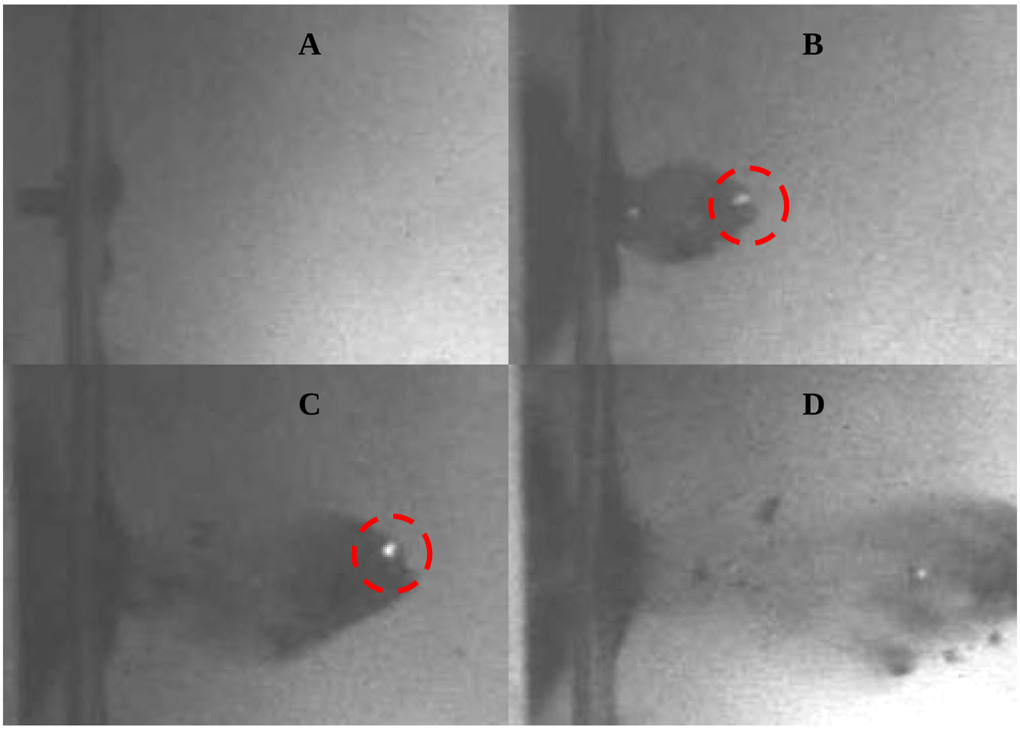

Figure 4. IMACON photographs showing the perforation of the M193 Ball projectile on 3.2 mm Mars 240. In the red dashed circle, a plug of Mars 240 material is visible.

RESULTS FROM NUMERICAL SIMULATIONS

With the use of the explicit numerical code Autodyn, several simulations are performed to help understand the results shown in Figure 1. The focus of the simulations was the difference between the 5.56 M193 Ball and the 5.56 SS109 'AP' projectile against 6.4 mm Mars 240 armour steel. The material model of Mars 240 is based upon dynamic material characterisation [2] and consists of a shock equation of state, a Johnson-Cook constitutive model and a principle stress failure model. The material models for the projectiles are taken from the Autodyn material library.

The simulations showed the same trend as the experiments: the M193 Ball projectile penetrates while the SS109 projectile is stopped by the armour system. Figure

5 shows a possible explanation for this observed trend. Figure A and C show the failure behaviour of the steel target for respectively the SS109 and the M193 Ball threat. Figure B (SS109) and D (M193 Ball) show the velocity vectors of projectiles in a close up view.

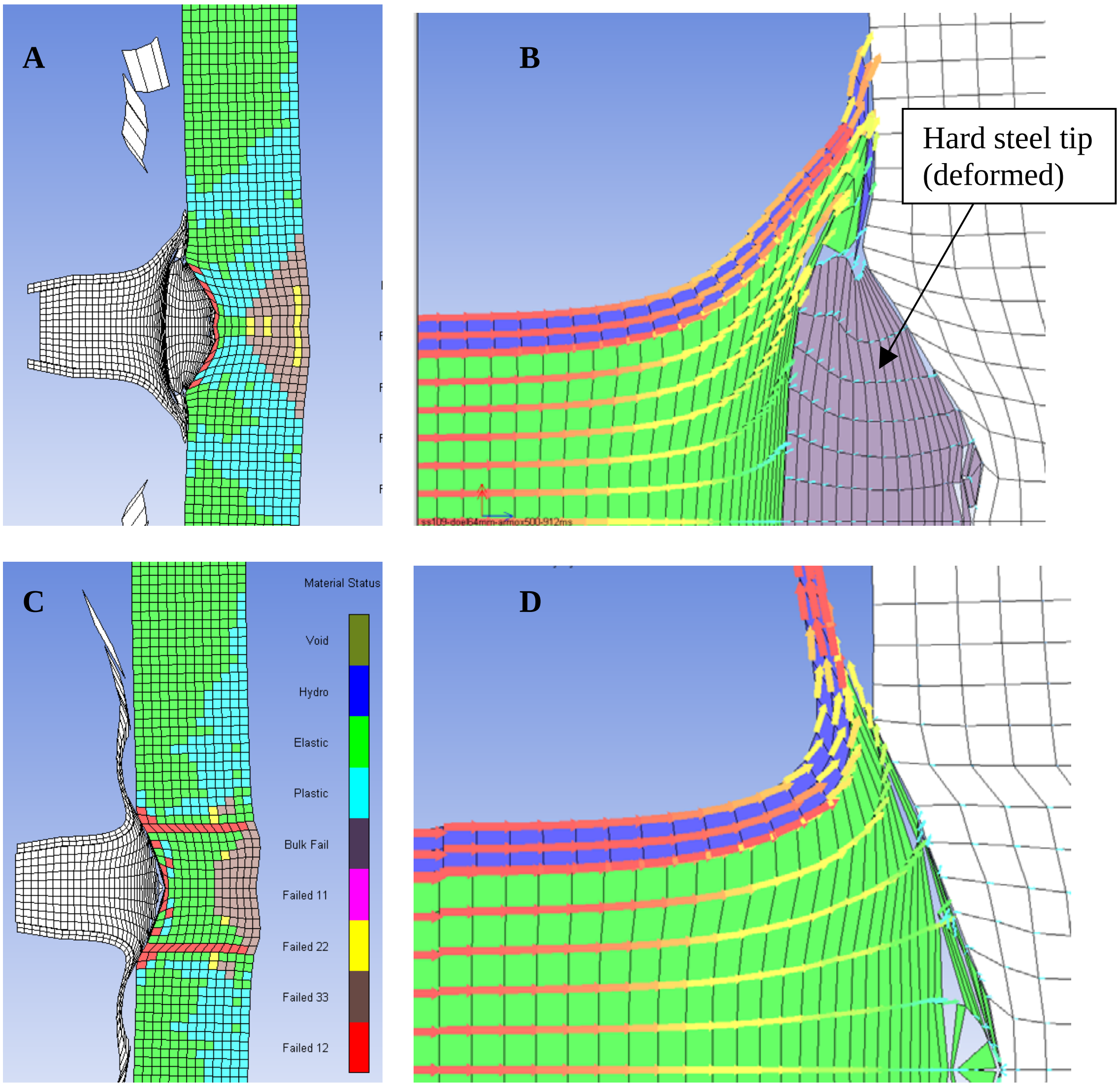

Figure 5. Figure A and C show the failure behaviour of the steel target for respectively the SS109 and the M193 Ball threat.
Figure B (SS109) and D (M193 Ball) show the velocity vectors of projectiles in a close up view (red colours > 800 m/s, yellow 500-700 m/s, green 300-500 m/s, blue < 300 m/s).

The failure behaviour of the target is clearly different for the two different projectiles. Figure 5A (SS109 impact) only shows tensile failure at the back surface of the target (spalling and cracking), while Figure 5C (M193 Ball) clearly shows shear failure (plugging). The plug which is formed is also visible on the IMACON photographs in Figure 4, indicated by the red dashed circle. These IMACON photographs are from an experiment with 3.2 mm of Mars 240, however the failure mechanism is comparable.

In Figure 5B and 5D an explanation can be found for the difference in failure behaviour of the target between an impact of a SS109 or a M193 Ball projectile. The response of the target is comparable for the first 10 µs of the impact. However after these first 10 µs, the target still encounters a great momentum from the M193 Ball projectile in contrast to the SS109 projectile. This can be seen in Figure 5D, where the back side of the projectile moves forward with more than 800 m/s and all energy necessary to diverge this ‘stream’ of lead material sideward originates from the target. Furthermore, the target surface involved is small (equal to the projectile calibre).

In Figure 5B however, the ‘stream’ of lead material is diverged sideward by the hard steel tip of the SS109 projectile, making the target surface involved larger (approximately twice the projectile calibre). In this process part of the kinetic energy is also dissipated by the deformation of the hard steel tip. Summarising, less energy is transferred to the target material and the momentum is transferred over a larger target area, resulting in no shear failure (plugging) of the target and no perforation.

DISCUSSION

The results from the experiment with the 7.62x39 API-BZ show that an Al/Steel armour system performs better than an Steel/Al armour system against the 7.62x39 API-BZ. A possible explanation for this result can be found when one thinks of stripping the jacket off the projectile core. Both in the steel-front target and in the aluminium-front target, the jacket is stripped off. However, since the steel is much harder than the aluminium the stripping of the jacket is less energy absorbing than the stripping in the aluminium target. Therefore, the projectile has lost more kinetic energy in the aluminium-front target than in the steel-front target.

An extra effect is that the residual core in the steel-front target, which perforates the aluminium, is not affected much by the aluminium since the core has a good L/D ratio and the aluminium is soft. On the other hand, the residual core in the aluminium-front target, which perforates the steel, is affected much more by the steel, since steel is much harder than aluminium.

That the stripping of the jacket can have a big influence on the performance of an armour system is also seen in previous research [3]. In this research numerical simulations are made of a 7.62x51 NATO AP projectile with 830 m/s penetrating 30 mm of aluminium. The residual velocity of the hard steel core of the projectile was

67% lower when the jacket of the projectile was modelled joined to the hard steel core than when the jacket was modelled as a separate part, making stripping of the jacket easier.

Advantages of this phenomenon can also be seen in [4]. This research shows that a magnesium alloy armour (ZK60A) with a surface weight of 110 kg/m^2 has a V_{50} [5] for the 7.62 NATO AP which is 7% higher than the V_{50} of an aluminium armour (Al5083) with the same surface weight (110 kg/m^2). This can also be due to the fact that the magnesium alloy does not strip the jacket off the projectile while the aluminium alloy does.

CONCLUSION

With the use of experiments and numerical simulations it is shown that a hard top layer does not always have to be the optimal choice for protection against small calibre projectiles. It is shown that the 5.56 mm M193 Ball can be a heavier threat for a hard top armour than the 5.56 SS109 ‘AP’. Furthermore an aluminium/steel armour system can perform better than a steel/aluminium armour system. This can occur for projectiles with a relatively soft jacket in comparison to the core material. One can optimise the armour system by taken into account the stripping of the jacket.

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