Performance enhancement of armour steel against blunt projectiles using pre-layers

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Abstract

Damage containment is one of the key factors for optimising operational readiness of warships after an internal warhead detonation. Ship designers currently have no other option than to rely on state of the art solutions applied in vehicle and personal protection; mainly ballistic composites. These solutions are prone to being traded off during the design process due to cost of the bulk material. Areas to protect are in the order of magnitude of hundreds of square meters. This called for development of a cost efficient, but lightweight protection against fragments.

TNO has teamed up with industrial partners to develop understanding of the physical phenomena involved in pre-layers on armour steels [1], in order to optimise protective solutions. Goal of the project was to assess the potential of using polymer coated armour steels in combination with blast bulkheads. The project consisted of three iterations of testing and analysis. The first test programme was aimed at understanding the physics explaining why armour steels perform significantly better against blunt projectiles when covered with an additional thin layer of a relatively soft material. Knowledge from the preliminary tests was applied to protective concepts for blast bulkheads. The pre-layer on the armour steel allows it to dissipate the energy over a wider area of the steel. In the experiments extreme stretching of the armour plate occurred and about twice the amount of energy is dissipated in the armour steel compared to the uncoated situation. The work resulted in protective concepts that fulfilled the mass requirements and are based on affordable materials. The project team considers this technology to be promising for future application in warships. Solutions from this project will be engineered further into a prototype concept. There is spin-off possible to other platforms like vehicles and offshore rigs, where mass and cost are equally important.

Keywords: fragment protection, lightweight, affordable, ship protection, pre-layers, polymers, armour steel.

1. Introduction

Damage containment is one of the key factors for optimising operational readiness of warships after an internal warhead detonation. Over the past decades, TNO has developed blast resistant bulkheads and doors [2]. Protection against fragments has not seen the same level of development, and naval ship designers have no other option than to rely on solutions applied in vehicle and personal protection; mainly ballistic composites. These solutions are prone to being traded off during the design process due to high cost of the bulk material. Areas to protect are in the order of magnitude of hundreds of square meters. This called for development of a cost efficient, but lightweight protection against fragments. Partners in this project are:

- Bolidt Synthetic Products & Systems
- Damen Schelde Naval Shipbuilding
- Netherland Ministry of Defence – Defence Materiel Organisation
- De Graauw Trading
- IHC Merwede – Dredging & Mining
- Ruukki Metals Oy
- TNO Defence Research

2. Goal

Goal of the project was to assess the potential of using polymer coated armour steels in combination with blast bulkheads, as a lightweight and affordable alternative for ballistic composites. Dedicated ballistic materials currently on the market are either too heavy or too expensive to apply in the large quantities required for ships.

3. Approach

The project consisted of three iterations of testing and analysis. The first test programme was aimed at understanding the physics explaining why armour steels perform significantly better against blunt projectiles, when covered with an additional thin layer of a relatively soft material. Knowledge from the preliminary tests was applied to protective concepts for blast bulkheads in two subsequent test series. The results of those test series are merged in this paper.

4. Requirements

4.1. Fragment protection

Royal Netherlands Navy has criteria for fragment protection against typical medium sized anti-ship missiles, in terms of percentage of the fragments hitting a bulkhead allowed to perforate. This percentage is determined by a functional analysis of the compartment adjacent to the detonation compartment, with the fragment protected blast bulkhead in between. This criterion translated into a 20 mm FSP (53 gram) at a velocity of 1600 m/s (68 kJ) that needs to be stopped. For reference: the energy of a 0.50” projectile fired from a Browning Machine Gun is 10-14 kJ.

4.2. Cost

The criteria for cost are defined by comparison with regular watertight (WT) bulkheads. Maximum allowable cost for a protected bulkhead are:

- 3,5 times cost/m² of a regular WT bulkhead, including insulation;
- 0,5 times cost/m² of a regular WT bulkhead, including insulation, including 2 x 20 mm aramid fragment protection;
- 3 times cost/m² of a conventional blast bulkhead, including insulation;
- 0,5 times cost/m² of a conventional blast bulkhead, including insulation, including 2 x 20 mm aramid fragment protection;

Aramid is chosen as the benchmark material because of its performance/price ratio. In short, our solution based on coated armour steel must be at least twice as cheap.

4.3. Mass

The criteria for mass are also defined by benchmarking against a regular watertight bulkhead:

- 3 x mass/m² of a regular WT bulkhead, including insulation;
- 2 x mass/m² of a regular WT bulkhead, including insulation, including 2 x 20 mm aramid fragment protection;
- 2,5 x mass/m² of a conventional blast bulkhead, including insulation, excluding aramid fragment protection;
- 1,5 x mass/m² of a conventional blast bulkhead, including insulation, including 2 x 20 mm aramid fragment protection;

5. Results

5.1. Ramor 500 against 0.50” FSP

The armour steel that was used throughout our experiments was Ramor 500 from RUUKKI, Finland. Its specifications are given in Table 1.

Table 1 Typical mechanical properties of RUUKKI Ramor armour steels

	Yield strength R MPa	Tensile strength R MPa	Elongation A %	Hardness HB	Impact strength t °C	All directions Charpy V J
Ramor 500	1450	1700	7	480-560	-40	20

To understand the perforation mechanics we shot 0.50” Fragment Simulating Projectiles (FSP) on a bare Ramor 500 plate. The high speed stills given in Figure 1 give an overview of the mechanism: a plug is clearly pushed out of the Ramor plate.

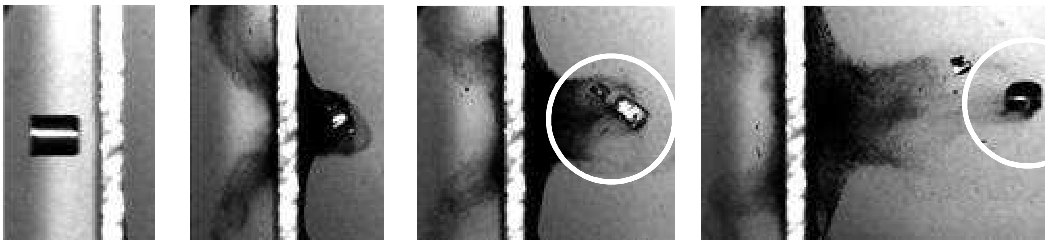


Figure 1 Sequence of high speed camera images for non-coated Ramor 500 (5 mm) impacted at 607 m/s by a 0.50” FSP: perforation of the steel by plug formation (white circle).

5.2. Effect of pre-layers on ballistic performance

Subsequently, we included a wide variety of pre-layers ranging from water to float glass. An indication of V_{50} was determined by four shots, two partial penetrations and two complete penetrations. The energy absorption by the Ramor 500 plate including the pre-layer is given in Figure 2. Energy absorption is related to the square of the V_{50}:

$$\text{Energy ratio} = E_{kin,\ coated}/E_{kin,\ bare\ Ramor\ 500} = V^2_{50,\ coated}/V^2_{50,\ Ramor\ 500}.$$

In the graph it is compensated for the mass by dividing by the areal mass of the coated plate. The graphs shows that basically any pre-layer gives a large increase in energy absorption, and specifically the harder materials perform well (judging from the PVC and float glass results). The pre-layer on the armour steel allows it to dissipate the energy over a wider area of the steel. Plug formation is delayed to higher energy regimes. In the experiments extreme stretching of the armour plate occurred and about twice the amount of energy is dissipated in the armour steel compared to the uncoated situation. For application in explosion resistant bulkheads, our preference goes to either polyureas or polyurethanes, because of their manufacturability and the experience with polyurethanes in deck coatings.

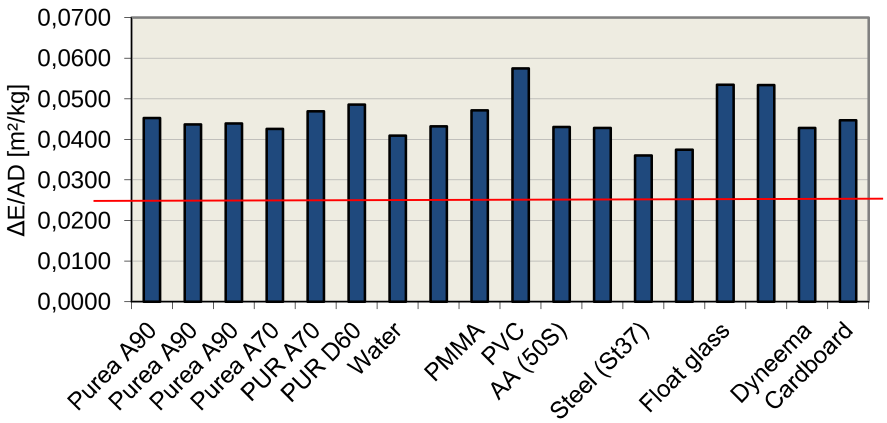


Figure 2 Energy ratio over areal density [m^2/kg]. 5 mm bare Ramor 500 = 0.0256 given by the red line.

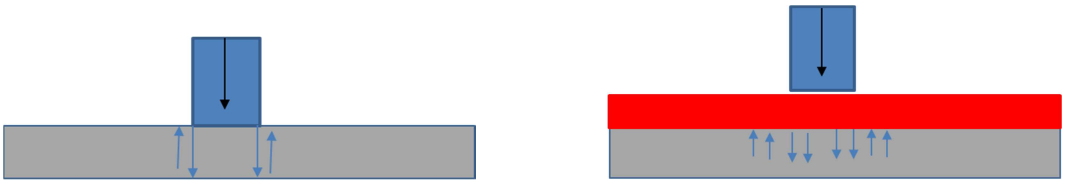


Figure 3 Impact damage and a shear stress gradient (blue arrows) within a armour steel plate at the periphery of a direct (left) and indirect (using a pre-layer)

5.3. Ballistic concepts for blast bulkheads

Based on the knowledge from the initial trials concepts for ballistic protection of blast bulkheads were developed. We selected the polyureas and polyurethanes with hardness equal to that of PVC, while keeping track of other properties like manufacturability and maintenance: polyurea A90 and polyurethane D80. For protection of a double blast bulkhead, a polymer coated Ramor plate is placed in between the ship steel (S355) plates. For protection of the single blast bulkhead, a plate of polymer coated Ramor can be placed either in front of the bulkhead or behind the bulkhead. The concepts are schematically shown in Figure 4. Test setup is given is Figure 5 with photos of the gun and target in Figure 6.

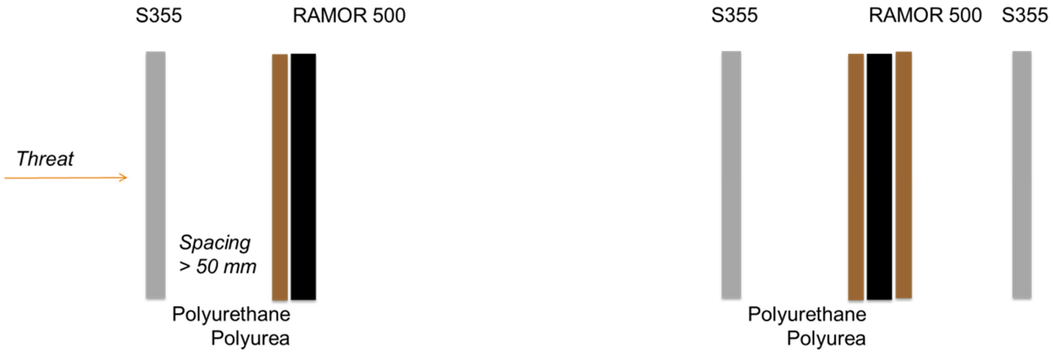


Figure 4 Left: One-directional solution for single blast bulkhead. Right: Bi-directional solution for double blast bulkhead.

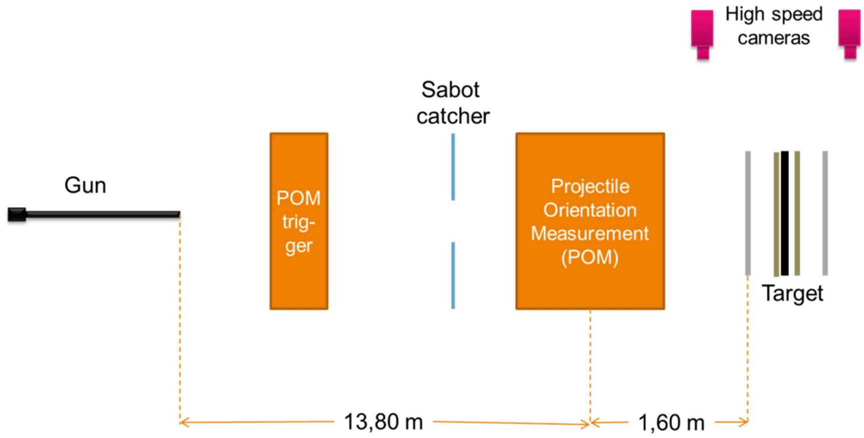


Figure 5 Setup for testing fragment protection of blast bulkheads

Figure 6 Overview of the gun and target setup.

Table 2 Results of concept testing, threat is 20 mm FSP at around 1600 m/s

Hit °	Schematic configuration	Areal mass [kg/m²]	Vhit [m/s]	CP/PP	Vrest [m/s]
0		167	1617	PP	
0		167	1620	PP	
0		167	1626	PP	
30		167	1622	PP	
30		167	1614	PP	
30		151	1629	CP	400
0		153	1605	PP	
0		132	1615	PP	
0		116	1621	PP	
0		132	1621	CP	750
0		116	1616	PP	
0		117	1619	PP	
0		119	1600	CP	800
0		140	1620	CP	350
0		140	1606	CP	250

Polyurea Polyurethane D80 Polyurethane D60 S355 LRA Ramor 500 Air gap

From Table 2 it can be seen that a combination of S355 plates in the double bulkhead, protected by a coated Ramor 500 plate fulfills the requirement of stopping a 20 mm FSP at 1600 m/s. Furthermore, it can be seen that a spacing is required for maximum performance of the pre-layer: the stacked sequence of ship steel and coated Ramor shows a complete penetration with a residual velocity of 750 m/s. When applying spacing and even reducing the thickness of the ship steel plate shows a partial penetration. In reverse order, with the coated Ramor plate at the impact side of the bulkhead to be protected, the pre-layer is less effective. The FSP perforates with 800 m/s residual velocity. The bulkhead on impact side slows the FSP down and deforms it such that the coated armour steel plate is highly effective. Thickness is required in the Ramor plate, since a concept of coated plates at halve the thickness on both sides of the bulkhead plate clearly does not work (last two shots). Shots show complete penetrations and residual velocities of up to 350 m/s. The areal masses of around 120 kg/m^2 are very competitive regarding this energetic threat. It was not tested in this research, but based on the Thor relations a single plate of 275 kg/m^2 S355 steel would give the same level of protection.

During some of the shots the test setup was equipped with additional X-RAY imaging. It shows details invisible on (high speed) visual cameras. The photograph in Figure 7 shows an overlay of the penetration in two instances in time. The ship steel plate is the bright line on the left, the sandwich of polymer and Ramor plate the bright line in the middle. The first X-ray instance shows the FSP just after perforating the ship steel plate, it is heavily deformed by impacting with 1600 m/s on the plate. The second instance shows the deformed Ramor plate by the bright dent nearly in the middle of the photo. The somewhat vaguer arc behind it is the dynamic stretching of the polymer layer behind the Ramor plate. The photo on the right shows the dent in the Ramor plate, which stretches across 10-15 cm. Because of the high tensile strength of Ramor 500, this amount of stretching dissipates an enormous amount of energy. Much more than the plugging energy from the bare Ramor plate as seen in Figure 1.

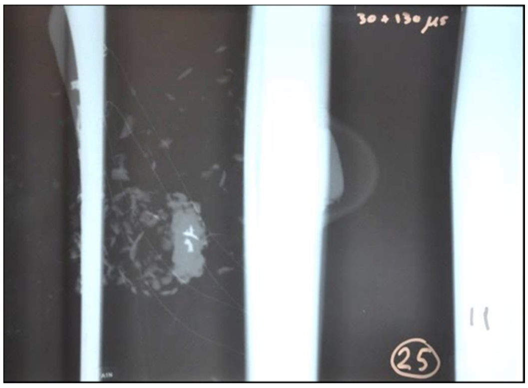


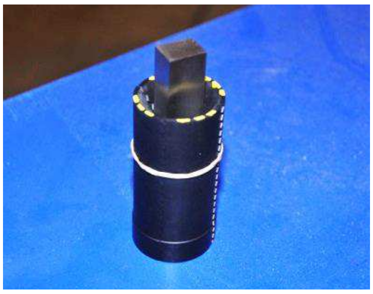
Figure 7 Denting of the RUUKKI Ramor 500 plate

5.4. Verification against design criteria
Single blast bulkhead: 47 kg/m²
Protected single blast bulkhead: 116 kg/m²
This is about 2½ times the mass of the unprotected bulkhead, which meets the requirement.

Double blast bulkhead: 94 kg/m²
Protected double blast bulkhead: 169 kg/m²
This is about 1.8 times the mass of the unprotected bulkhead, which is well within the requirement.

Cost assessment is complex as this requires knowledge on the manufacturing process and the ability to scale up the application process. This will be topic of subsequent development, where we take the technology readiness to higher levels by building a demonstrator. Based on the cost of bulk material alone the armour steel/polymer combination recommended in this paper is about three to four times lower compared to ballistic composites like aramid.

5.5. Verification of results against bar projectiles
Most of fragment testing these days is done using FSPs. In order to assess how sensitive results are on the shape of the fragment, an additional test series were performed using bars. The shape of the bar is based on breakup of a warhead casing, making use of the simulation code SPLIT-X. Mass of the RVS 316 bar is identical to that of a 20 mm FSP, 53 grams.



51 × 13,3 × 10 mm
RVS 316
53 gram

Figure 8 Bar projectile in composite sabot

Three out of eight shots perforated the target that stopped the 20 mm FSP. The angle of impact between the longitudinal axis of the bar and the target is relatively small in those three cases. This means that the mass is concentrated on a small impact area, resulting in high local pressure on the target. A correlation between yaw angle and penetration capacity was found. The orientation of the bar in the gun is such that the impact will lead to a worst case, with most of the mass behind a small impact area. However, it shows that results from FSP testing must not be taken by face value. Arena testing of selected fragment protection concepts with a genuine warhead is recommended.

6. Conclusions

- Increase in energy absorption when using a pre-layer on armour steel is very promising, with values of around 2. The polymer/Ramor combination dissipates twice the amount of energy with respect to the same plate of Ramor alone at only slight mass increases, in the order of 10%.
- Polymer pre-layers with high hardness show better ballistic performance than pre-layers with low hardness.
- For bulkhead protection, spacing is necessary to allow deformation of the FSP before hitting the coated armour plate. When stacked together, efficiency is less.
- We have candidates for ballistic protection for both single and double blast bulkheads, that comply with fragment, mass and (most likely) cost criteria.
- Compliance with other requirements depends on further engineering of the product.

The project team considers this technology to be promising for future application in warships. Solutions from this project will be engineered further into a prototype concept. There is spin-off possible to other platforms like vehicles and offshore rigs, where mass and cost are equally important.

7. References

1 C.M. Roland, D. Fragiadakis, R.M. Gamache 2010. “Elastomer–steel laminate armor”, *Composite Structures* **92** 1059–1064

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