Passive Protection of Unarmoured Objects

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Abstract. This article presents problems related to passive composite protection of unarmoured objects (helicopters, vehicles, etc.). It is focused on building and testing the different add-on armours (panels) protecting unarmoured objects against small-arms armour piercing projectiles (kinetic energy - KE). It has been illustrated how to increase ballistic protection of composite armours with minimum mass for unarmoured objects. The selection of appropriate materials and their parameters affects the improvement of the protection capability of these panels. The different parameters of ceramic samples (Al$_2$O$_3$, SiC, Ti$_3$SiC$_2$, B$_4$C) which were used for the panels are presented. Panels sized of 100×100 mm contained the different types of layers, eg. polyethylene, aluminum sheet and small sized ceramics plates (50×50 mm and thickness of 6 mm, 8 mm and 9 mm), etc. The tested panels were placed in a small frame and the rear surfaces of the panels were at a distance from „witness RHA” (Rolled Homogeneous Armour). The protection capability of panels for all types of tests were defined with the use of 5.56×45 mm SS109 HC projectiles (STANAG 4569), which reference depth of penetration was $D_{ref}=8$ mm RHA.

1. Introduction

Military helicopters are built under different types of requirements. There are processing of the technical documentation according to ASD S1000D standard [1], MIL-STD-38784 [2] specification (Department of Defense Standard Practice for Manuals, Technical: General Style and Format Requirements - 25 Aug. 2011).

These types of helicopter have several required elements to provide situational awareness and armour protection. For example, the SPS-TA V2 [3] provides enhanced EW situational awareness and self-defence (active and passive threats). The sensors of this system detect the threat, track and counter with a flare.

The Birdie 118 (1×1×8") and 218 (2×1×8") infrared bispectral bait are specially balanced infrared (IR) flares [4]. By replicating the helicopter signature in the mid-wave IR, Birdie baits at attracting modern air-to-air missiles (SAMs and AAMs) with dual-colour ratio discrimination. Birdie's effectiveness is proven and operationally validated. Optional helicopter equipment can be used with various types of laser warning receivers and interfaces for an optional infrared illuminator and/or radio frequency jammer.

Another helicopter’s protection is crashworthiness, the design of which cannot prevent an accident/incident, but it will protect passengers (or other vulnerable cargo) against impact. Helicopter component protection may be: energy absorbing materials in construction and seats, self-healing crashworthy fuel tanks, seat attenuator and slide system and airbags and harness restraint systems.

The protective layers usually protect: the floor, side protection, seats, cockpit and other relevant components such as the engine, etc. For example, the NH 90 and Tiger were realised in accordance...
with STANAG 4569 and customer specifications \cite{4}. Rheinmetall Chempro provides lightweight protection for helicopters using, among other things, composite materials.

VERHA-Air (Versatile Rheinmetall Armour) military object protection is made using coated aramid materials, high performance polyethylene and glass fibre \cite{4}. For higher levels of protection, these materials can be used with different types of ceramic layers.

In the event of a potential threat to the helicopter, suitable armour - steel and/or light armour - should be used for the passive protection of the crew, the people carried and for the protection of some mechanical and electronic equipment. For example, the Mi-17 helicopter \cite{5} is equipped with composite and steel armour (Figure 1) for protection against AK-47, AK-74, M-16 and other missiles (Table 1).

**Figure 1.** Protection of Mi 7: a, b - outside aerodynamically shaped ceramic composite panels, b - layout of Dyneema panels and armoured steel plates on the cockpit floor, c - front panel with bullet-proof glass situated in the front panel \cite{5}.

| Item                        | Quantity, pcs | Ballistic resistance | Shot gun, ammunition, velocity, range | Material               |
|-----------------------------|---------------|----------------------|---------------------------------------|------------------------|
| Armoured steel plates       | 2             | III+                 | • 308 Winch, 7.62×51 NATO Ball, 15 m  | Armox 500 carbon steel |
| (floor protection)          |               |                      | • AK-47, 7.62×39 MSC, 715 m/s, 20 m   |                        |
|                             |               |                      | • M-16, 5.56×45 SS109, 1000 m/s, 20 m |                        |
|                             |               |                      | • AK-74, 5.56×39 MSC, 870 m/s, 20 m   |                        |
| Bullet-proof glass          | 1             | III                  | • 308 Winch, 7.62×51 NATO Ball, 15 m  | Multilayer armoured glass |
| (front protection)          |               |                      | • AK-47, 7.62×39 MSC, 715 m/s, 20 m   | SiC + aramid           |
| Ceramic composite panels    | 6             | III+                 | • 308 Winch 7.62×51 NATO Ball, 15 m   | Dyneema HB26/HB5 0     |
| (side protection)           |               |                      | • AK-47 7.62×39 MSC, 715 m/s, 20 m    |                        |
|                             |               |                      | • M-16, 5.56×45 SS109, 1000 m/s, 20 m  |                        |
|                             |               |                      | • AK-74, 5.56×39 MSC, 870 m/s, 20 m   |                        |
| Dyneema panels              | 12            | III+                 | • 308 Winch, 7.62×51 NATO Ball, 15 m  | Dyneema HB26/HB5 0     |
| (floor protection)          |               |                      | • AK-47, 7.62×39 MSC, 715 m/s, 20 m   |                        |
|                             |               |                      | • M-16, 5.56×45 SS109, 1000 m/s, 20 m  |                        |
|                             |               |                      | • AK-74, 5.56×39 MSC, 870 m/s, 20 m   |                        |
| Dyneema panels              | 2             | III+                 | • 308 Winch 7.62×51 NATO Ball, 15 m   | Dyneema HB26/HB5 0     |
| (overhead protection)       |               |                      | • AK-47, 7.62×39 MSC, 715 m/s, 20 m   |                        |
|                             |               |                      | • M-16, 5.56×45 SS109, 1000 m/s, 20 m  |                        |
|                             |               |                      | • AK-74, 5.56×39 MSC, 870 m/s, 20 m   |                        |
| Ceramic composite           | 4             | III+                 | • 308 Winch 7.62×51 NATO Ball, 15 m   | SiC + aramid           |
| (overhead protection)       |               |                      | • AK-47, 7.62×39 MSC, 715 m/s, 20 m   |                        |
| panels                     |               |                      | • M-16, 5.56×45 SS109, 1000 m/s, 20 m  |                        |
|                             |               |                      | • AK-74, 5.56×39 MSC, 870 m/s, 20 m   |                        |

IBCOL Composites GmbH in 2005 published that for crisis control and other military operations it is necessary to protect the crew of the TIGER helicopter from 7.62×51 mm AP (P80) and 12.7×99 mm API (P1947) calibre projectiles \cite{6}. Other examples of helicopter and aircraft protection using passive
protection against small arms projectiles are presented in [7-10], and protection against projectiles fired from RPG-7 is shown in [11].

2. Materials for helicopter protection

For preparing the tests of composite armours some of the ceramic plates parameters were checked (Table 2).

Table 2. Parameters of ceramic plates

| Kind of ceramics | Al₂O₃ 99.7% | Al₂O₃ 97% | Al₂O₃ 96.8% | Al₂O₃ 96.2% | Al₂O₃ 99%M | Ti₃SiC₂ | SiC | B₄C |
|------------------|-------------|----------|-------------|-------------|-----------|--------|-----|-----|
| Density, ρ (g/cm³) | 3.915       | 3.68     | 3.726       | 3.68        | 3.76      | 4.3    | 3.0 | 2.35 |
| Hardness, HV (GPa) | -           | -        | -           | Mo 9        | -         | 8      | 22  | 30  |
| Bending strength, σ (MPa) | -           | -        | -           | 350         | 300       | 250    | 350 | 250 |
| Young’s modulus, E (GPa) | 378.86      | 329.7    | 320.5       | 333         | -         | 340    | 400 | 380 |
| Modulus of elasticity in shear, G(GPa) | 153.92      | 133.37   | 129.8       | -           | -         | 140    | 200 | 160 |
| Crack resistance, KIC (MPa m⁰.⁵) | -           | -        | -           | 6.2         | -         | 10     | 3   | 2.5 |
| Poisson’s ratio, ν | 0.231       | 0.236    | 0.234       | -           | 0.188     | 0.15   | 0.16 |
| Thermal conductivity coefficient (W/mK) | -           | -        | -           | 21          | 26.8      | 50     | 60  | 20  |
| Longitudinal sound speed, C_L (m/s) | 10 597      | 10 116   | 10 017      | -           | -         | -      | -   | -   |
| Transverse sound speed, C_T (m/s) | 6 270       | 5 946    | 5 904       | -           | -         | -      | -   | -   |

Knowing the measured ceramic parameters C_L, C_T (Table 2), the parameters E, G, ν were calculated according to the following formulas:

\[ E = \rho C_L^2 \frac{3C_L^2 - 4C_T^2}{C_L^2 - C_T^2} \]  \( (1) \)

\[ G = E/2(1+\nu) \]  \( (2) \)

\[ \nu = \frac{C_L^2 - 2C_T^2}{2(C_L^2 - C_T^2)} \]  \( (3) \)

where: ρ - density, C_L - longitudinal sound speed, C_T - transverse wave speed, E - Young’s modulus, G - modulus of volume elasticity, ν - Poisson ratio.

For example, Al₂O₃ (99 %) ceramics was chosen for manufacturing the plates of different dimensions and density (Table 3), which were used for building helicopter’s passive armours.

Table 3. Dimensions and density of Al₂O₃ (99 %) ceramic plates

| No. | Dimensions (mm) | Density, ρ (g/cm³) |
|-----|-----------------|--------------------|
| 1   | 50×50×8         | 3.88               |
| 2   | 50×50×10        | 3.87               |
| 3   | 50×50×12        | 3.90               |
| 4   | 50×50×18        | 3.88               |
| 5   | 100×100×30      | 3.74               |
| 6   | 100×100×40      | 3.88               |

3. Armours’ tests
The aim of the research was to obtain a minimum mass of the armour, made in the form of a closed panel on all sides. Such a panel is designed to protect an unarmoured object of a very light and thin structure against penetration by various small-arms projectiles - 5.56×45 mm SS109 HC (Hard Core). This mainly concerns the protection of a helicopter with a thin - 1÷3 mm aluminum construction. For that reason, the shot-fired back surface of panels was placed 150 mm away from the 335×335×4 mm “RHA witness” plate (RHA - Rolled Homogeneous Armour).

Panels with surfaces of 100×100 mm, were prepared for testing. Ceramic plates with the parameters presented in Tables 2, 3 were used in these panels. In order to obtain a projectile stop in the examined panel, the type and thickness of panel layers were being changed.

The Tables 4 - 8 and Figures 2 - 9 show examples of stopping the projectile in panels with the smallest masses or examples of panels pierced by the projectile. On the “RHA witness” plate only a trace of the hitting projectile or fragments of it with a depth of ~1 mm was achieved. In case of application of a different type of armour (panel), the inner layer of the protected object can be additionally protected with a spall liner (Kevlar, etc.).

Initially, the aim of the research was to test the protective capability of composite panels with dimensions of 100×100 mm and different thicknesses.

The panels contained different types of layers, such as polyethylene, aluminium sheet and Al₂O₃ ceramic tiles with small dimensions 50×50 mm and thickness: 6 mm, 8 mm and 9 mm.

Panels of composite armours were installed on the panel stand (Figure 2) and were fired at the angle of \( \alpha_{\text{NATO}}=0^\circ \) from normal to panel’s surface. The distance between the end of ballistics gun, mounted on the gun stand and panel’s surface was 3 m in order to achieve maximum speed of projectiles.

![Figure 2. View of the test station: 1 - gun stand, 2 - ballistics gun, 3 - panel stand, 4 -“witness RHA”, 5 - small frame, 6 - distance support, 7 - panel, 8 - corner cramp](image)

For testing different passive armours the 5.56×45 mm SS109 HC projectiles were used (Figure 3, Table 4).
**Figure 3.** Standard NATO intermediate ammunition 5.56×45 SS109 HC

**Table 4.** Data of 5.56x45 SS109 HC projectile

| Cartridge: 5.56×45 /.223 Rem. | Muzzle velocity: 945 m/s |
|-------------------------------|--------------------------|
| Projectile: HC, 4.0 g / 62 g  | Muzzle energy: 2020 J    |
| Projectile material: tombac jacket, hardened steel and lead core | Penetration at 570 m: 3.5 mm steel plate, Rockwell b55÷70 (~ 8÷10 mm RHA at 5 m) |
| Ballistic coefficient: C1 0.310 (ICAO) | Term of reference: MCMOPI |
| Primer / propellant: SINOXID / double base powder | Accuracy at 300 m: sh; sv ≤ 85 mm |
| Case material: CuZn alloy | Temperature range: -54°C to +52°C |
| Cartridge weight: 12.2 g | Mean case mouth pressure: + 3 s max. 4 450 bar (21°C) |

This projectile is one of the best-in-class accuracy which significantly outperforms NATO-standards and reliable under extreme environmental conditions.

The reference depth of penetration of these projectiles was $D_{P_{ref}}=8÷10$ mm RHA.

Initially, among the many composite panels’ tests performed, the projectiles with kinetic energy of the 5.56x45 mm SS109 HC were used.

In the tested panels (variant 1) 50×50 mm small size Al₂O₃ ceramic plates, carbon fabric reinforced resin and foam (porosity 60÷70 %, area density $S=2÷2.5$ kg/m²) layer (Table 5, Figure 4, 5).

**Table 5.** Panels 100×100 mm (variant 1) after firing by 5.56×45 mm SS109 HC projectile

| No. of panel | Thickness of Al₂O₃ plate, mm / $S$, kg/m² | Thickness of Al foam, mm / $S$, kg/m² | Total thickness, mm | Area mass, $S$, kg/m² | Result of firing |
|--------------|------------------------------------------|--------------------------------------|---------------------|-----------------------|------------------|
| 12           | 6 / 24                                   | 10 / 2                               | 16                  | 26                    | Pierced panel, trace on the RHA |
| 13           | 8 / 32                                   | 8/1.6                                | 16                  | 33.6                  | Pierced panel, trace on the RHA |
| 14           | 6 / 24                                   | 16/3.2                               | 22                  | 27.2                  | Projectile stopped in the panel |
| 15           | 8 / 32                                   | 9/1.8                                | 17                  | 33.8                  | Pierced panel, trace on the RHA |

**Figure 4.** Pierced panels 12 and 13 with the trace on the RHA (a - front side, b - rear side)
Figure 5. Pierced panel 14 and 15 which stopped projectile and panel 15 with the trace on the RHA (a - front side, b - rear side)

Next the panels (variant 2) were tested, which included: 50×50 mm small-size Al₂O₃ ceramic plates, Kevlar layers and resin-reinforced carbon fabric (Table 6, Figures 6 - 8). The ceramic plates were bonded to the Kevlar (area density $S = 1 \, \text{kg/m}^2$) layer.

Table 6. Panels 100×100 mm (variant 2) after firing by 5.56×45 mm SS109 HC projectile

| No. of panel | Thickness of Al₂O₃ plate, mm / $S$, kg/m² | Number of Kevlar layers / $S$, kg/m² | Total thickness, mm | Area mass, $S$, kg/m² | Result of firing |
|--------------|------------------------------------------|-------------------------------------|---------------------|----------------------|------------------|
| 17           | 8 / 32                                   | 5 / 5                               | 13                  | 37                   | Pierced panel, trace on the RHA |
| 18           | 6 / 24                                   | 14 / 14                             | 20                  | 38                   | Projectile stopped in the panel |
| 20           | 6 / 24                                   | 14 / 14                             | 20                  | 38                   | Projectile stopped in the panel |
| 21           | 6 / 24                                   | 13 / 13                             | 19                  | 37                   | Projectile stopped in the panel |
| 22           | 6 / 24                                   | 15 / 15                             | 21                  | 39                   | Projectile stopped in the panel |

Figure 6. Pierced panel 17 with the trace on the RHA (a - front side, b - rear side), and panel 18 which stopped projectile (c - front side, d - rear side)

Figure 7. Panels 20 and 21 which stopped projectile (a - front side, b - rear side)

Figure 8. Panels 22 which stopped projectile (a - front side, b - rear side)
Next, the panels (variant 3) were tested that contained: polyethylene, 50×50 mm small-size Al₂O₃ ceramic plates, Kevlar layers, resin-reinforced carbon fabric and PA9 sheets (Table 7, Figure 9). The ceramic plates were bonded to the Kevlar layer, and 6 of these layers connected the front and back surfaces of the panel.

Table 7. Panels 100×100 mm (variant 3) after firing by 5.56×45 mm SS109 HC projectile

| No. of panel | Layer 1: polyethylene thickness, mm / S, kg/m² | Layer 2: thickness of Al₂O₃ plate, mm / S, kg/m² | Layer 3: thickness, mm / S, kg/m² | Total thickness, mm, S, kg/m² | Result of firing |
|--------------|-----------------------------------------------|-----------------------------------------------|---------------------------------|-------------------------------|-----------------|
| 23           | 1 / 1                                         | 9 / 36                                        | Kevlar 9 / 9                    | 19 / 46                       | Projectile stopped in panel |
| 24           | 1 / 1                                         | 9 / 36                                        | Kevlar 4.5 / 4.5                | 14.5 / 41.5                   | Projectile stopped in panel |
| 25           | 1 / 0.9                                       | 9 / 36                                        | PB9 sheet / 3 / 3              | 13 / 39.9                     | Projectile stopped in panel |

Figure 9. Panels 23-25 which stopped projectile: a - front side, b - rear side

4. Conclusions

On the basis of research, the biggest protective capabilities were achieved with the use of:

Al₂O₃ with the following parameters: high content of ≥ 99 %, density ρ ≥ 3.88 g/cm³, hardness Hv ≥ 17 GPa, bending strength σ ≥ 330 MPa, compression strength σ ≥ 2.4 GPa, Young’s modulus E ≥ 350 GPa, modulus of volume elasticity G ≥ 128 GPa, resistance to brittle cracking Kic ≥ 5 MPam⁰.₅, Poisson ratio ν ≥ 0.23, large speed of longitudinal wave CL ≥ 9660 m/s and transverse wave CT ≥ 5740 m/s;

The minimum area density of panels with the above-mentioned ceramic tile parameters which stopped 5.56×45 mm SS109 HC projectiles depends on the panel design and manufacturing technology (Table 8).

Table 8. Parameters of panels with minimum area density which stopped 5.56×45 mm SS109 HC projectiles

| Variant | No. of panel | Layer 1 / thickness, mm | Layer 2 / thickness, mm | Layer 3 / thickness, mm | Total thickness, mm | Area mass, kg/m² |
|---------|--------------|--------------------------|-------------------------|-------------------------|---------------------|------------------|
| 1       | 14           | Al₂O₃ / 6                | Al foam / 12            | -                       | 22                  | 27.2             |
| 2       | 21           | Al₂O₃ / 6                | Kevlar / 14             | -                       | 19                  | 37               |
| 3 | 25 | Polyethylene / 0.9 | Al2O3 / 9 | PB9 sheet / 3 | 13 | 39.9 |

5. References

[1] http://www.s1000d.org (accessed January 2021)
[2] http://www.everspec.com (accessed January 2021)
[3] https://www.thalesgroup.com/en/self-protection-system-sps-ta (accessed January 2021)
[4] https://www.rheinmetall-defence.com/en/rheinmetall_defence/systems_and_products/protection_systems/protection_systems_air/index.php (accessed January 2021)
[5] http://www.asubaltija.com (accessed January 2021)
[6] Sliwinski M, Kucharczyk W, Guminski R 2018 Overview of polymer laminates applicable to elements of light-weight ballistic shields of special purpose transport Means Scientific Journal of the Military University of Land Forces 50 228-243
[7] Small arms defense against air attack subcourse number is 4401, Edition C United States Army Air Defense Artillery School, Fort Bliss, Texas 79916-3802, 2 Credit Hours, May 2006 (accessed January 2021)
[8] Plonka B, Senderski J, Wisniewski A 2011 Light metal-ceramic passive armour for special application Proceedings of 26th International Symposium on Ballistics, Miami, USA, September 12-16, DEStech Publications, Inc., USA, Bibliography ISBN13: 978-1-60595-052-5, pp 1576-1587
[9] https://www.qinetiq.com/en-us/what-we-do/services-and-products/last-armor-aircraft-and-land-protection-armor (accessed January 2021)
[10] High Performance Fibres BV. DSM. (n.d.), (online). Dyneema (website). Available at: (accessed September 2018)
[11] Wisniewski A 2006 Possibility of protection of helicopters against projectiles launched from RPG-7 Problemy Techniki Uzbrojenia Poland 97 15-23