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Hybride Composite Armour Systems with Advanced Ceramics and Ultra-High Molecular Weight Polyethylene (UHMWPE) Fibres

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Abstract
The aim of the research was to develop a new concept of hybride composite armour systems consisting of a ceramic and fibrous composite. Depending on the requirements for ballistic protection, armour systems may be designed to various configurations and weights based on the most suitable ceramic materials and backing. The article describes the development of a hybrid ceramic - multi-layered ultra-high molecular weight polyethylene (UHMWPE) composite armour made from silicon carbide (SiC) or aluminium oxide (Al_2O_3) of different thicknesses (3.0, 3.5, 4.0, 4.5, 17.27 and 13.35 mm) and shapes (hexagonal and cylindrical) in combination with a polyethylene fibrous composite. Additionally research work developed a confinement system for the hybrid ceramic - multi-layered UHMWPE composite armour which significantly improves the ballistic performance of composite armour by creation of a uniform compression condition of the ceramic and by reducing its fragmentation upon impact. The ballistic armour strength was tested according to the PN-V-87000:2011, NIJ 0101.04 standard and NATO STANAG 4569 (AEP-55 Vol.1) standard for protection against more than one shot (multi-hit). The hybrid ceramic - multi-layered UHMWPE composite armour was combined with basic fibrous ballistic armours which exhibited a ballistic strength compatible with level IIIA according to the NIJ 0101.04 standard and classes K2 and O3 according to the PN-V-87000: 2011 standard.

Key words: *composite armour, bullet proof vest, multi-hit, non-oxide ceramics, silicon carbide (SiC), aluminium oxide (Al_2O_3), ultra-high molecular weight polyethylene (UHMWPE) fibres.*

Introduction

Several new composite materials have been introduced to improve ballistic armour performance, including fibrous composites and ceramics. There is an increasing demand for these materials and other multilayer material systems that provide maximum ballistic protection with minimal mass. Over the years, ceramics and polymer matrix composites have found increasing use in armour protection systems for improving the efficiency of light to medium armour [1 - 8]. Composite armour systems, which are also known as multi-layered armour systems, contain frontal plates composed of hard-disrupting materials such as ceramics (e.g., alumina, silicon, boron carbide and quartz) and backing faces composed of ductile materials (e.g., steel, aluminium alloy, fibrous composites or polycarbonate) [1]. Upon ballistic impact with a projectile velocity > 700 m/s, the hard ceramic body can be cracked and broken, but a metal alloy backing plate will absorb the remaining kinetic energy of the projectile through plastic deformation. In the case of a metal alloy or fibre reinforced composite, these can undergo elastic deformation and damage, where a ceramic backing plate must also support post-impact fracturing [9]. On the other hand, ductile materials convert the kinetic energy of the projectile into a lower energy form, such as heat, through inelastic deformation [10]. The mass of the composite armour is less than armour made of only ballistic steel. This is especially appealing when dealing with small-to-medium armour piercing calibres (e.g., AP 7.62 mm or AP 12.7 mm) [10, 11]. When a projectile impacts and penetrates the ceramic face, brittle failure ensues, leading to extensive fragmentation of the tile. However, if failure involves extensive fragmentation of the tile or the fragments are not retained in place, the multi-hit capability of the armour can become compromised [12]. When ceramic facing is used as a single layer covering the entire back plate, the ballistic efficiency is higher due to the greater lateral confinement of the impact area. However, the damage caused by the projectile may extend over the entire ceramic surface, whereas with small tiles, this damage affects only the adjacent ones [13]. In this case, the backing plate deformation process absorbs most of the energy (approx. 20 - 40%) from the bullets, while an insignificant amount of energy (approx. 0.2%) is absorbed by the fracture of the ceramic plate. As reported by den Reijer [1], premature fragmentation of the ceramic tile reduces its erosive capacity and, consequently, the ballistic efficiency of the armour. The rest of the kinetic energy is spent to deform the projectile (10 - 15%) and a vast amount of energy is dissipated by the ceramic debris ejected [14 - 15]. Many modern-day armours are regularly subjected to automatic weapons fire, where multiple bullets are fired towards a single location. Thus for multi-hit protection it is necessary to keep as much of the ceramic material intact as possible after each hit. This can be achieved by reducing the tile size such that if one tile has been destroyed by a single projectile, the area exposed to subsequent strikes is minimised. Reducing the tile size inevitably leads to an increase in the number of interfaces between the tiles for a given area [12]. Bless and Jurick [16] conducted a probability-based analysis of such mosaics to determine how multi-hit protection varies with tile size. They concluded that an increase in the number of interfaces is likely to influence the performance of an armour system. Protecting against multiple impacts requires a mosaic of small cells. The cell size can be computed from a statistical analysis of the number of impacts accepted over a given area. In most cases, interface impacts are very likely; however, any effects on armour performance can be accommodated for with good design. De Rosset [17] examined the protective capacity of composite armours against automatic weapon fire and showed that the armour was vulnerable at the joints between individual cells. However, to properly interpret these analyses, one must know how the ballistic performance is affected by the proximity of the impact to the tile edge. Without this knowledge, only crude assumptions can be made. There is little published work on the effect of tile size and shape on the ballistic performance of composite armours. However, researchers have studied the effect of applying radial confinement on the behaviour of a ceramic tile under dynamic loading conditions. Sherman [18] examined the impact on a confined ceramic tile using a 7.62 mm (0.30”) armour piercing projectile and showed that the addition of a steel confinement frame significantly reduced damage to the tile, whereas using other supporting materials of lower acoustic impedance led to greater ceramic tile damage [18]. Others have shown that adding steel radial confinements to ceramics subjected to high velocity long rod penetration also results in greater resistance to penetration [19, 20]. The shape and size of the tile is also important for ballistic testing of ceramic materials. Wide reviews on the various techniques for testing armour materials are provided by James [21] as well as Normandia and Gooch [22]. There are clear advantages to using small tiles, not only in terms of the cost of the ceramic but also with respect to that of the backing materials. Therefore it is advantageous to know the smallest tile size that will provide the most accurate data for a material’s ballistic resistance. Michael and Kibbutz [23] described a cylindrical ceramic body for deployment in composite armour systems. The hard ceramic pellets provide a multiplicity of surfaces in the structure and, thus, a multiplicity of crack initiation sites. Due to the cylindrical shapes of the ceramic pellets, the cracks could not propagate too far within the cylinders (i.e., the cylinders significantly improve energy dissipation upon ballistic impact). In this type of armour, the projectile always faces a new surface of the hard material [23]. However, in most cost-effective mosaic armour designs, the sides of the tiles are unlikely to be ground flat. Therefore there will be little to no intimate contact between tiles. Thus in order to evaluate the worst case scenario it should be assumed that each tile is performing independently of its neighbour [12]. In a high performance scenario, the primary objective should be to reduce the weight of the structure for the intended usage, and the effect of the target thickness on the ballistic impact performance becomes an important consideration for further investigations. Riou [24] performed experiments on composite armours with different ceramic layer thicknesses. A significant degradation of the ceramic was observed in a normal impact test (AP12.7 mm), in which fragmentation was caused by tensile hoop stresses and strains induced by the radial motion of the ceramic after impact.

The aim of this research was to develop a new concept of hybrid ballistic materials consisting in a ceramic and fibrous composite. The thesis of the research covers the idea of the appropriate selection of materials layers for armour yielding an improvement in the ballistic behavior of the final multilayered, hybrid ballistic amour. Suitable selection of the types of fibrous materials as well as the shape, thickness and confinement of the ceramic should affect the ballistic properties of the resultant multilayered, hybrid ballistic armour.

Materials

Ceramic materials

For the production of the hybrid ceramic - multi-layered ultra-high molecular weight polyethylene (UHMWPE) composite armour, hexagonal ceramics were used made of silicon carbide (SiC) (ESK Ceramics GmbH & Co. KG, Germany) and aluminium oxide (Al_2O_3) (Barat Ceramics GmbH, Germany). The tests also used cylindrical ceramics based on silicon carbide (Ningbo Kylin Machinery Co, Limited, China). Technical parameters for characterising the ceramic products are summarised in ***Table 1***.

Table 1. *Characteristics of the hexagonal and cylindrical ceramics.*

No	Ceramics		Density, g/cm^3 [25, 26, 32]	Thickness, mm PBM-33/ITB:2008 [25]	Areal density, kg/m^2 PBM-17/ ITB:2008 [26]
1	Hexagonal ceramic SiC		3.0 ± 0.1	3.01 ± 0.01	3.6 ± 0.1
2				4.01 ± 0.01	4.5 ± 0.1
3				4.45 ± 0.01	4.8 ± 0.1
4	Hexagonal ceramic Al_2O_3		3.6 ± 0.1	4.49 ± 0.01	6.0 ± 0.1
5	Cylindrical ceramic SiC		3.0 ± 0.1	17.27 ± 0.01	6.6 ± 0.2
6				13.35 ± 0.01	6.3 ± 0.2

Polyethylene materials

Three types of polyethylene materials with ultra-high molecular weight polyethylene (UHMWPE) (DSM High Performance Fibbers BV, The Netherlands) were used to manufacture the hybrid ceramic - multi-layered UHMWPE composite armour. Their parameters are shown in ***Table 2***.

In metrological tests of the polyethylene materials, the structural parameters and strength of the materials were determined taking into account the final properties of

Table 2. *Technical parameters of UHMWPE materials used to manufacture the hybrid ceramic - multi-layered UHMWPE composite armour.*

No	Parameter	Unit	UHMPWE			Testing procedure
			Dyneema® SB21	Dyneema® SB51	Dyneema® HB26	
1	Width	cm	161.0 ± 0.2	161.0 ± 0.2	160.0 ± 0.1	PN-EN ISO 2286-1:2000 [27]
2	Areal density	g/m^2	147 ± 1	258 ± 1	262 ± 1	PN-EN ISO 2286-2:1999 [28]
3	Thickness	mm	0.18 ± 0.01	0.29 ± 0.01	0.36 ± 0.01	PN-EN ISO 2286-3:2000 [29]
4	Breaking force: -lengthwise -crosswise	kN	6.0 ± 0.1 5.9 ± 0.2	10.8 ± 0.5 11.0 ± 0.4	9.37 ± 0.24 8.48 ± 0.21	PN-EN ISO 1421/1:2001 [30]
5	Elongation at break: -lengthwise -crosswise	%	3.8 ± 0.1 4.0 ± 0.1	4.2 ± 0.1 4.6 ± 0.1	3.6 ± 0.1 3.2 ± 0.1	PN-EN ISO 1421/1:2001 [30]
6	Tear resistance: -lengthwise -crosswise	N	there is not tearing	there is not tearing	there is not tearing	PN-EN ISO 4674-1:2005 [31]

the ballistic products that they were used to make. From the point of view of assessing the quality and usefulness of the ballistic materials, the following key structural parameters were tested:

- linear dimensions, i.e., width, length and thickness,
- areal density,
- density of the warp and weft.

Additionally the most important strength parameters affecting the quality of the ballistic products were used as indicators of tensile strength and tear resistance. Based on the metrological tests (***Table 2***), we confirmed that the polyethylene textile materials used in the construction of the hybrid ceramic – multi-layered UHMWPE composite armour had appropriate structural parameters, tensile strengths and tear resistance according to the manufacturer's technical specification. Thus these materials possess the ballistic strength required for hybrid composite armour.

Additional materials

For the hybrid ceramic - multi-layered UHMWPE composite armour of the hexagonal ceramics/composite fibre type, silicone adhesive was used for a temperature range of 20 to 25 °C (Henkel Polska Sp. z o. o.). In order to increase the strength of the bonded joints, the composite surface layer was chemically purified using an adhesion promoter with a density of 0.74 ± 0.1 g/cm^3, a viscosity at 20 °C of 2 m Pa·s and an absorption time of 60 seconds (Henkel Polska Sp. z o. o.).

The system confinement was formed from technical textile mesh with a mesh size of 0.4 mm x 0.4 mm, a layer of adhesive film (based on silane polymer), areal density 200 ± 5 g/m^2 (Bochemia, Poland), p-aramid-phenolic prepreg (one-sided) Twaron® CT736, 1680dtex, areal density 200 ± 5 g/m^2 (Teijin, Japan), and foamed material with an adhesive layer of FORMAT-GKS-3/SA/EXTRA of cellular diameter 5 ± 0.1μm and thickness of at least 1 mm (Interchemall, Poland). For the fabrication of hybrid ceramic - multi-layered UHMWPE composite armour of the cylindrical ceramics/composite fibre type, flexible casting polyurethane UR 3440 was used (Amor, Poland) along with polymeric microspheres with a diameter of 40 m and density of 25 kg/m^3 (Eka Chemicals AD, Expancel, Sweden). Flexible polyurethane was mixed directly with the polymer microspheres with the addition of 2.5 parts by weight of polymer microspheres per 100 parts by weight of polyurethane. Crosslinking took place at 40 °C for 48 hours.

Testing methods

Assessment of the mechanical properties

Mechanical properties of the polyethylene materials were tested according to the following standards: PN-EN ISO 2286-1:2000 [27], PN-EN ISO 2286-2:1999 [28], PN-EN ISO 2286-3:2000 [29], PN-EN ISO 1421/1:2001 [30] and PN-EN ISO 4674-1:2005 [31]. The results are given in ***Table 2***. The areal density and thickness of the hybrid ceramic – multi-layered UHMWPE composite armour were measured in accordance with the following test procedures: PBM-33/ITB:2009 [25], PBM-17/ITB:2008 [26] and Standard PN-EN ISO 1923:1999 [32]. The thickness of the ceramic material was determined using a thickness gauge with a pressure force of 2 ± 0.2 kPa. The total areal density in g/m^2 was calculated by determining the weight in g and surface area of the test sample in mm^2.

Assessment of ballistic properties

The ballistic strength of the hybrid ceramic – multi-layered UHMWPE composite armour was measured in accordance with PN-V-87000:2011 [33], NIJ 0101.04 [34] and a test procedure modelled on NATO STANAG 4569 (AEP-55 Vol. 1) [35], which describes a method for testing ballistic armours to protect against more than one shot (i.e., the multi-hit procedure). According to this procedure, each sample is impacted with a series of at least 6 shots. The first impact point was determined at random from within the working area designated by PN-V 87000:2011 [33]. After firing the first shot, another impact point was set away from the first hit point by 25 + 2 mm. After the second shot, the median of the segment connecting impact points 1 and 2 was determined. A distance of 50 mm from this segment at an angle of 60° was used as the third impact point. Firing was continued until exhaustion of the test area of the sample. The maximum distance allowable between the hit points was 25 + 2 mm. The range of ballistic tests carried out in accordance with the methodology of Standard PN-V-87000:2011 [33], NIJ 0101.04 [34] and the multi-hit procedure is shown in ***Table 3*** (see page 82).

Nuclear magnetic resonance (NMR)

The ^{1}H- and ^{13}C-NMR spectra were obtained using a Bruker Avance III 400 Wide Bore (9.4 T) instrument (Bruker, Germany) recorded for samples of Dyneema®HB26 in the solid phase.

Fourier transform infrared spectroscopy (FTIR) tests

FTIR tests were performed using a NICOLET IS10 spectrophotometer (Thermo Scientific, USA) using the attenuated total reflection (ATR) method in the range

Table 3. Requirements for ballistic strength of the hybrid ceramic - multi-layered UHMWPE composite armour.

Type of armour	Ballistic class/level	Standard	Ammunition
Basic ballistic armour	O3	PN-V-87000:2011 [33]	FSP 22
	K2		7.62 TT FMJS
	III A	NIJ 0101.04 [34]	44 MAGNUM SJHP
			9 mm FMJ RN
Hybrid ceramic - multi-layered UHMWPE composite armour (used in conjunction with NIJ 0101.04/IIIA [34]; PN-V-87000:2011/K2/O3 [33] Vest)	K3	PN-V-87000:2011 [33]	7.62×39 mm PS
			5.56×45 mm SS109 (STANAG 4172 [36])
			7.62×51 mm FMJS
	special class	PN-V-87000:2011 [33]	4.6×30 mm AP
	multi-hit procedure	NATO STANAG 4569 (AEP-55 Vol.1) [35]	7.62×39 mm PS
			5.56×45 mm SS109 (STANAG 4172 [36])
			7.62×51 mm FMJS
	K5	PN-V-87000:2011 [33]	7.62×51 mm AP

of 400 to 4000 cm^{-1}. For the FTIR-ATR testing, the material was to cut to dimensions of 20 × 20 mm and applied to the crystal by pushing it down in a suitable manner. Both the background spectrum (i.e., the spectrum of the crystal) and the spectrum of the crystal with the sample were measured. The background measurement was saved in the internal memory of the spectrophotometer and automatically subtracted from the sample measurement to be correct for the external conditions of the tests.

X-ray tests - analysis of damage to the surface of the hybrid ceramic – multi-layered UHMWPE composite armour

Non-destructive flaw detection as well as structural and material tests of the hybrid ceramic - multilayered UHMWPE composite armour (Dyneema®HB26) were carried out using a real-time radioscopy (RTR) system - MU 225-9 17F made by Yxlon International X-ray, Germany. X-ray tests were performed at the Military Institute of Armament Technology (Zielonka, Poland). X-ray images of the samples were analysed in Imagine J software to determine the area of destruction of the composite armour after impact. The Image J analysis consisted of reading the image of the sample, manually outlining (in the program) the visible area of damage and digitally measuring the surface of this area in pixels. The actual surface of the area was determined from the conversion of the image resolution using a linear scale photographed in an identical system as a reference. Imagine J is public domain software (National Institutes of Health USA) and is available at http://imagej.nih.gov/ij [2015-07-20].

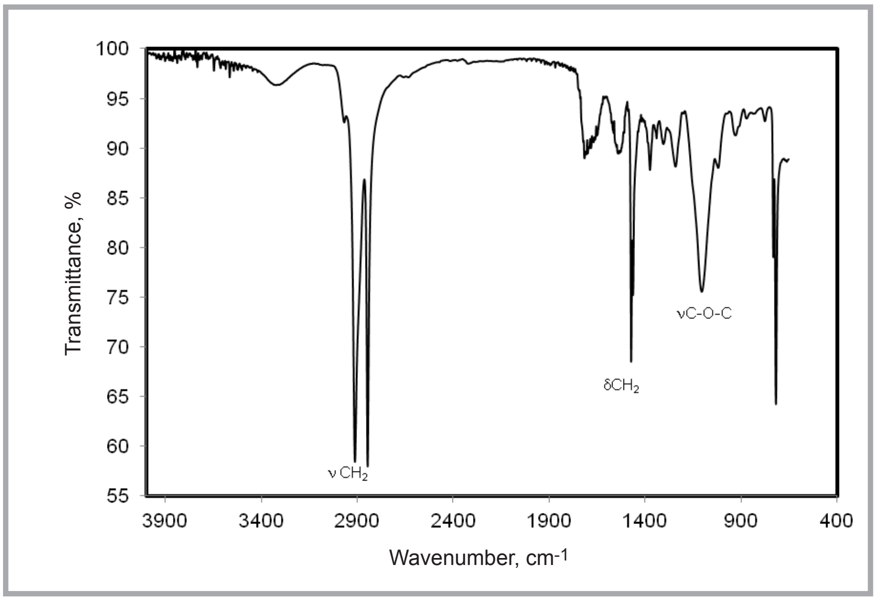

Figure 1. FTIR spectrum of Dyneema®HB26.

Armours preparation

Basic ballistic armour (soft armour)

Basic ballistic armour (soft armour) with dimensions of 300 × 360 mm was assembled using UHMWPE products: Dyneema®SB51 and Dyneema®SB21 (DSM High Performance Fibbers BV, The Netherlands). The basic ballistic armour had an areal density between 5 and 7 kg/m^2 depending on the type of UHMWPE fibre used.

Hybrid ceramic - multi-layered UHMWPE composite armour

The hybrid ceramic - multi-layered UHMWPE composite armour (Moratex, Poland) consisted of pressed multilayer polyethylene plates and ceramics. Pressed multilayer polyethylene plates were prepared by compressing UHMWPE polyethylene Dyneema®HB26. In order to select the most optimal conditions for compressing the Dyneema®HB26, we identified the warp forming part of the starting material of Dyneema®HB26 located on the surface of this material. Spectroscopic data (FTIR-ATR, NMR) from the analysis of Dyneema®HB26 were taken in the form of numerical data. Only some characteristic signals could be selected from the experimental data because the focus was not on the technical side of the spectral analysis and the spectrum only identified the molecular structure of the warp of the Dyneema®HB26 material. The FTIR-ATR spectra of Dyneema®HB26 (***Figure 1***) contained absorption bands corresponding to the vibration of the following molecular moieties:

- CH_2 (2911 cm^{-1}, 2845 cm^{-1}; 1470 cm^{-1}; 730 cm^{-1}),
- CH_3 (1370 cm^{-1}, 1340 cm^{-1}),
- COC (1100 cm^{-1}).

The nature of the FTIR-ATR spectrum of the material tested indicates the presence of moieties indicative of polyethylene. In addition the spectrum shows a characteristic intense band at 1100 cm^{-1}, which is most likely associated with the stretching vibration of the CO bonding. The oxygen atom caused a shift in the absorption frequency of the neighbouring CH_2 groups in relation to their positions in the hydrocarbons, as evidenced by the band at 1520 cm^{-1}, corresponding to the deformation vibration in the plane of the methylene group.

Confirmation of the presence of the CO moiety can be found in the ^{13}C NMR spectrum (***Figure 2***), where in the aliphatic range of chemical shifts there are four carbon signals. The two peaks at 74.48 ppm and 72.47 ppm are due to the carbon sp^3 hybridisation with oxygen. Another signal at 31.45 ppm corresponds to carbon-carbon bonding. The signal at 16.94 ppm can be attributed to the methyl groups. In turn, the ^1H NMR spectrum (***Figure 3***) of the test material shows signals from the protons of CH_2 groups in the range of 2.20 to 2.90 ppm and CH_3 groups in the range of 1.00 to 1.75 ppm. In addition, the FTIR-ATR spectrum had a band at 1700 cm^{-1}, which most likely resulted from vibrations of the CO groups belonging to the saturated esters (CO = 1735 - 1750 cm^{-1}) and saturated ketones (CO = 1705 - 1725 cm^{-1}). However, confirmation of the presence of CO moieties was not found in the ^{13}C NMR spectrum, where there were no signals at 170 ppm corresponding to carbon atoms from the CO group. In the course of the analysis above, it can be concluded that the binder for Dyneema®HB26 material is a polyurethane-ethereal polymer. Data obtained on the chemical structure of the binder allowed for the selection of optimal processing conditions for the Dyneema®HB26 material. The compression process took place in several stages and involved pre-compression (T = 130 °C), main compression (T = 130 °C) and cooling (T = 130 - 65 °C). The compression pressure was approximately 20 MPa. The hybrid ceramic - multi-layered UHMWPE composite armour had an areal density in the range of 23 to 30 kg/m^2. These armours were intended for use in combination with basic ballistic armour with a ballistic strength in accordance with NIJ 0101.04/IIIA [34] and PN-V-87000:2011/K2/O3 [33]. The hybrid ceramic - multi-layered UHMWPE composite armour based on cylindrical ceramics were intended for independent use.

Hybrid ceramic - multi-layered UHMWPE composite armour based on hexagonal ceramics

The ceramic - multi-layered UHMWPE composite armour based on hexagonal ceramics contained pressed multilayer polyethylene composites and hexagonal ceramics based on silicon carbide or aluminium oxide (***Table 4***).

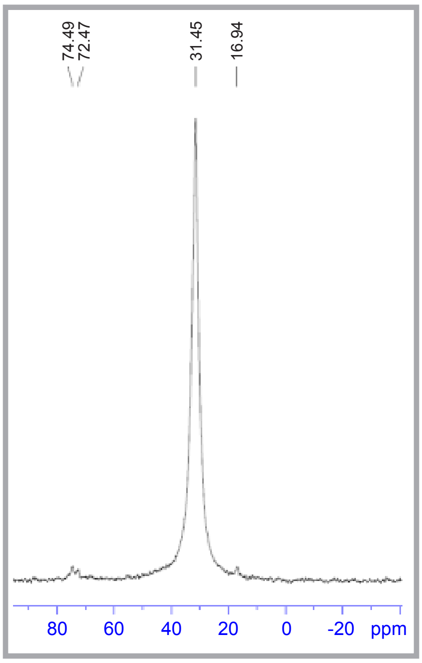

Figure 2. *^{13}C NMR spectrum of Dyneema® HB26.*

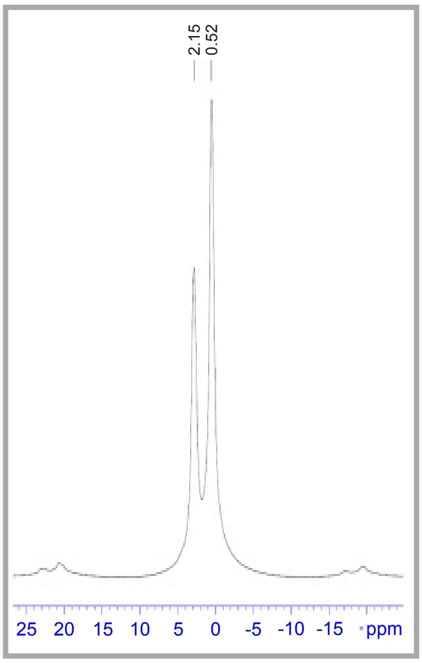

Figure 3. *^1H NMR spectrum of Dyneema® HB26.*

Hybrid ceramic - multi-layered UHMWPE composite armour based on cylindrical ceramics

The ceramic - multi-layered UHMWPE composite armour based on cylindrical ceramics was a layered material comprised of a pressed multilayer polyethylene board and cylindrical ceramics made from silicon carbide (***Table 5***). The ceramic - multi-layered UHMWPE composite armour made from cylindrical ceramics had an areal density of 42 to 54 kg/m^2 depending on the diameter of the cylindrical ceramics used. The ceramic and fibrous components were connected by way of flexible casting polyurethane 3440 UR filled with 40 μm diameter polymer microspheres with a density of 25 kg/m^3 to reduce their areal density.

Results and discussion

Ballistic strength of the basic ballistic armour

The basic ballistic armour was developed on the basis of two types of polyethylene materials: Dyneema®SB21 and Dyneema®SB51. The ballistic tests (***Table 6***, see page 84) showed that the basic ballistic armour simultaneously protected against three types of ammunition specified in two different standards, i.e., PN-V-87000:2011 [33] and NIJ 0101.04 [34], assuming a depth of surface deformation less than 40 mm:

- with a 7.62 TT FMJ bullet weighing 5.5 g with a steel jacket and bullet-proof class K2 according to PN-V 87000:2011 [33] at a speed of

Table 4. *Composition of hybrid ceramic - multi-layered UHMWPE composite armour based on hexagonal ceramics.*

Basic ballistic armour (NIJ 0101.04/IIIA [34] and PN-V-87000:2011/K2/O3 [33])	Hybrid ceramic - multi-layered UHMWPE composite armour based on hexagonal ceramics			Areal density, kg/m^2
	UHMWPE	Ceramic (Thickness, mm)	silicone adhesive	
Dyneema® SB51	Polyethylene composite based on Dyneema® HB26	SiC (3.0 - 4.5)	silicone adhesive	23 - 26
		Al_2O_3 (4.5)		30

Table 5. *Composition of hybrid ceramic - multi-layered UHMWPE composite armour made from cylindrical ceramics.*

Hybrid ceramic - multi-layered UHMWPE composite armour based on cylindrical ceramics			Areal density, kg/m^2
Multi-layered UHMWPE composite based on Dyneema®HB26 (Areal density, kg/m^2)	Ceramic SiC (Thickness, mm)	Elastomeric matrix	
6	17.27	PUR/polymer microspheres	54
10	13.35		42

Table 6. *Bullet-proof properties of basic ballistic armour composed of Dyneema®SB21 and Dyneema®SB51: FMJ - Full Metal Jacket, SJHP - Solid-Jacket Hollow Point.*

Parameter	Dyneema®SB51				Dyneema®SB21			
	dry	wet	+50 °C	-40 °C	dry	wet	+50 °C	-40 °C
Areal density, kg/m^2	5.88	5.95	6.01	5.99	6.88	6.89	6.87	6.91
7.62×25 TT FMJ								
Perforation	NO	NO	NO	NO	NO	NO	NO	NO
Velocity, m/s	435	436	435	442	447	443	431	432
Deformation, mm	18.0	19.0	19.0	20.0	20.0	19.0	18.0	18.0
9×19 Para FMJ								
Perforation	NO	NO	NO	NO	NO	NO	NO	NO
Velocity, m/s	453	446	457	448	439	442	445	439
Deformation, mm	26.0	25.0	23.0	24.0	23.0	21.0	28.0	24.0
44 MAGNUM SJHP								
Perforation	NO	NO	NO	NO	NO	NO	NO	NO
Velocity, m/s	457	435	439	440	446	451	439	440
Deformation, mm	38.0	37.0	39.0	27.0	30.0	31.0	32.0	28.0

Table 7. *Fragment-proof properties expressed by V50 for basic ballistic armour composed of Dyneema®SB21 and Dyneema®SB51.*

Parameter/Material	Dyneema®SB51		Dyneema®SB21	
	dry	wet	dry	wet
Areal density, kg/m^2	5.95	5.94	6.87	7.09
V50, m/s	645	653	653	667

Table 8. *Ballistic strength (4.6×30 mm DM31AP) of hybrid ceramic - multi-layered UHMWPE composite armour after conditioning at 50 °C.*

No	Hybrid ceramic - multi-layered UHMWPE composite armour			Velocity, m/s	Deformation, mm	Perforation
		Ceramic (thickness)	Areal density, kg/m^2			
1	used in conjunction with NIJ 0101.04/ IIIA [34]; PN-V-87000:2011/ K2/O3 [33] Vest	SiC (3.0 mm)	22.9 ± 0.3	673	3	YES
2		SiC (4.0 mm)	25.6 ± 0.4	673	2	
3		SiC (4.5 mm)	26.0 ± 0.3	669	1	NO
4		Al_2O_3 (4.5 mm)	29.9 ± 0.3	667		

420 ± 15 m/s, the maximum depth of material deformation is 20 mm,

- with a 9 mm FMJ bullet with a lead core weighing 8.0 g and protection class IIIA according to NIJ 0101.04 [34] at a speed of 436 ± 9 m/s, the maximum depth of material deformation is 26 mm,
- with a 44 Magnum SJHP bullet weighing 15.6 g and protection class IIIA according to NIJ 0101.04 [34] at a speed of 436 ± 9 m/s, the maximum depth of material deformation is 39 mm.

The 44 Magnum SJHP bullets protection class IIIA according to NIJ 0101.04 [34], caused particularly large values of deformation of the test material. The depth of deformation on the Dyneema®SB51 armour was between 27 and 39 mm for these bullets depending on the test conditions. Another important parameter for the basic ballistic armour was class O3 fragment protection (standard fragment of a weight of 1.10 ± 0.03 g) according to PN-V-87000:2011 [33] ***(Table 7)***. Fragment tests were carried out in dry conditions after sprinkling for ballistic armour kits developed on the basis of Dyneema®SB21 and Dyneema®SB51. The V50 was within the range of 600 to 675 m/s. Thus the ballistic armour was fragment-proof class O3 in accordance with PN-V-87000:2011 [33]. The initial comparison of the basic ballistic armour was based on the areal density. For the same level of ballistic strength, the basic ballistic armour made of Dyneema®SB51 had a 15% lower areal density than the basic ballistic armour made of Dyneema®SB21. Another interesting parameter for comparison is the depth of deformation of the test material. When firing 7.62 mm TT FMJ bullets and 9 mm FMJ bullets with IIIA resistance according to Standard NIJ0101.04 [34], the depth of deformation of the test material was the same for Dyneema®SB51 and Dyneema®SB21. However, for 44 Magnum bullets with IIIA resistance according to NIJ Standard 0101.04 [34], the deformation depth of the test material decreased by approximately 12% for ballistic armour made of Dyneema®SB21 compared to Dyneema®SB51. The bulletproof and fragment-proof properties indicate that basic ballistic armour systems made from Dyneema®SB21 and Dyneema®SB51 meet the requirements of ballistic protection classes K2 and O3 according to PN-V-87000: 2011 [33] and class III according to NIJ 0101.04 [34], assuming a depth of deformation in the test material of less than 40 mm. Bearing in mind the requirements above for ballistic protection and taking into account the assumption that the weight of the products manufactured has to be as low as possible while maintaining all aspects of ballistic strength, the areal density should be the main criterion for selecting a material for basic ballistic armour. Therefore the best solution for basic ballistic armour is armour made of Dyneema®SB51.

Ballistic strength of hybrid ceramic - multi-layered UHMWPE composite armour based on hexagonal ceramics

Ballistic tests of hybrid ceramic - multi-layered UHMWPE composite armour based on hexagonal ceramics were conducted in accordance with the requirements of PN-V-87000:2011 [33] and NIJ 0101.04 [34] with respect to basic ballistic armour (NIJ 0101.04 [34] PN-V-87000:2011 [33]). The ballistic tests used 4.6 × 30 mm DM31 AP bullets. In the first stage, tests were conducted using a ballistic strength of firing of 4.6 × 30 mm DM31 AP on composite systems manufactured after conditioning at 50 °C (***Table 8***). Some examples of hybrid ceramic - multi-layered UHMWPE composite armour after ballistic testing with 4.6 × 30 mm DM31 AP ammunition according to PN-V-87000:2011 are presented in ***Figure 4***. The ballistic strength of the hybrid ceramic - multi-layered UHMWPE composite armour depended on the thickness of the ceramics. Systems containing hexagonal ceramics with a thickness less than 4.5 mm did not show the ballistic strength desired after impact with 4.6 × 30 mm DM31 AP bullets. The ballistic strength required was displayed by hybrid ceramic - multi-layered UHMWPE composite armour with a thickness of 4.5 mm in its structure for both SiC and Al_2O_3. However, the use of SiC reduced the areal density by approximately 13% compared to systems containing Al_2O_3. Thus the hybrid ceramic - multi-layered UHMWPE composite armour containing hexagonal ceramics with a thickness of 4.5 mm based on SiC was selected for further tests because of its lower areal density and desirable ballistic properties.

For this composite system, the following ammunition impact conditions were tested:

- 7.62 × 51 mm FMJ lead-core bullet with a steel jacket weighing 9.6 ± 0.1 g, at 840 ± 15 m/s,
- 5.56 × 45 mm SS109 lead-core bullet with a soft steel jacket, according to STANAG 4172 [36], weighing 4.0 ± 0.1 g, at 950 ± 15 m/s,
- 7.62 × 39 mm PS bullet with a soft steel core and a jacket made of a copper alloy weighing 7.9 ± 0.1 g, at 720 ± 15 m/s,
- 4.6 × 30 mm DM31 AP bullet weighing 2 g, at 670 ± 15 m/s.

The ballistics tests were carried out as specified in PN-V-8700:2011 [33], with four sets for each type of ammunition: dry, after sprinkling, after conditioning at -40 and +50 °C.

The depth of deformation of the test material based on SiC with a thickness of 4.5 mm ranged from 10 to 36 mm. The 7.62 × 39 mm FMJ ammunition resulted in very high values for deformation of 36 mm. However, as for all of the hybrid ceramic - multi-layered UHMWPE composite armour tested, there was no shot-through. Thus the hybrid ceramic - multi-layered UHMWPE composite armour with an areal density of 29.9 ± 0.3 kg/m^2 in combination with basic ballistic armour (NIJ 0101.04 [34]; PN-V-87000:2011 [33]) provides effective protection against the following types of ammunition: 7.62 × 39 mm PS, 5.56 × 45 mm SS109, 7.62 × 51 mm FMJ and 4.6 × 30 mm DM11 AP in accordance with PN-V-8700:2011 [33].

For the hybrid ceramic - multi-layered UHMWPE composite armour containing hexagonal ceramics with a thickness of 4.5 mm based on SiC, ballistic strength tests were also carried out in accordance with the multi-hit test method modelled on NATO STANAG 4569 (AEP-55 Vol.1) [35] using the following ammunition: 7.62 × 39 mm PS, 5.56 × 45 mm SS109 and 7.62 × 51 mm FMJ, after conditioning at 50 °C (***Table 9***, column b). In the case of repeated firing on the composite system using 7.62 × 51 mm FMJ ammunition, the desired ballistic strength was achieved, while for the next two cases, i.e., composite systems fired upon with 5.56 × 45 mm SS109 and 7.62 × 39 mm PS ammunition, there was no assumed ballistic strength, which is associated with shooting through the system. Ballistic tests on the hybrid ceramic - multi-layered UHMWPE composite armour in accordance with the multi-hit procedure showed that the zone of cracks in the ceramic plates was not limited to the plate immediately struck by the bullet, as was in the case of the hybrid ceramic - multi-layered UHMWPE composite armour carried out in accordance with PN-V-87000:2011 [33]. The plates adjacent to the impact zone underwent extensive damage, e.g., cracks and chipping combined with detachment on a significant area of the armour (***Figure 5***).

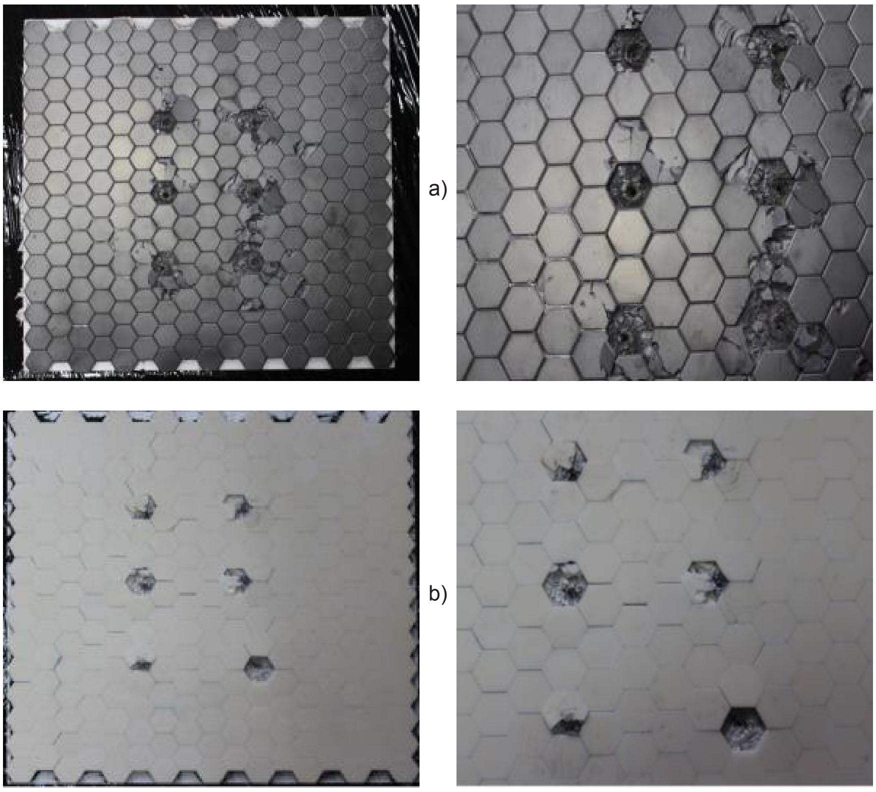

Figure 4. *Hybrid ceramic - multi-layered UHMWPE composite armour based on hexagonal ceramics of SiC (a) and Al_2O_3 (b) after ballistic tests using 4.6×30 mm DM31 AP ammunition according to [33].*

Figure 5. *Surface of the hybrid ceramic - multi-layered UHMWPE composite armour after ballistic testing by the multi-hit procedure using 5.56×45 mm SS109.*

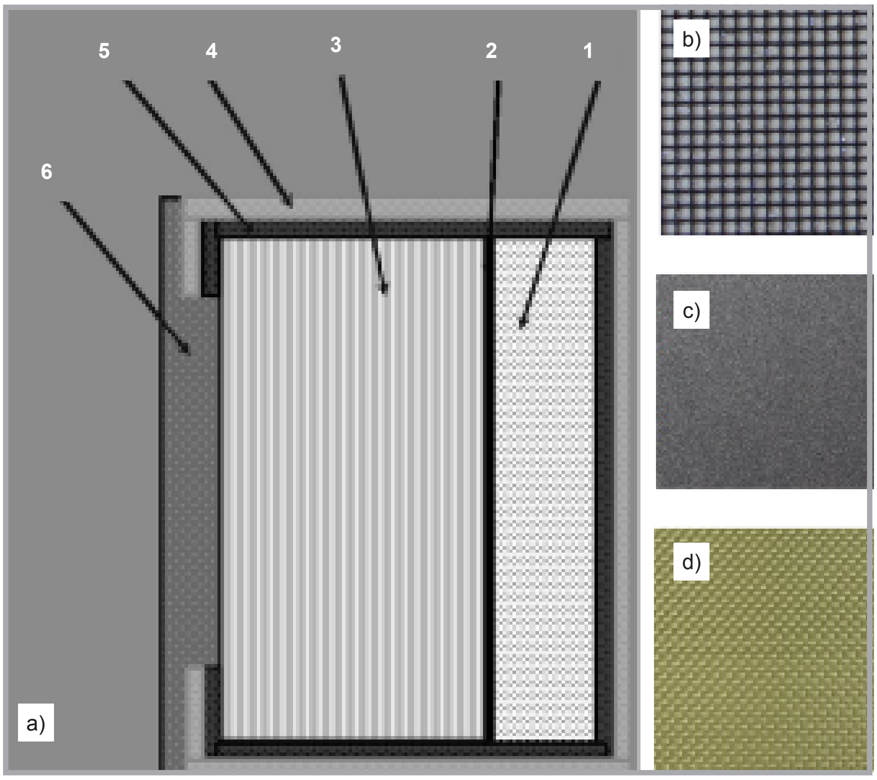

Figure 6. *Schematic design of system confinement of hybrid ceramic - multi-layered UHMWPE composite armour. Schematic design of the armour system (a), technical textile mesh (b), foamed material (c), p-aramid-phenolic prepreg (d); 1 – ceramic, 2 - silicone adhesive 3 - polyethylene composites 4- the technical textile mesh, 5 - p-aramid-phenolic prepreg, 6 - foamed material .*

Armour firing carried out in accordance with the multi-hit procedure significantly increased the scale of potential damage to the ceramic structure, which was surely caused by the small distance (25.0 mm) between the impact zones on the armour. It can be assumed that volumetric fracturing was one of the causes of damage in the ceramic material. In addition, striking the armour with a bullet generates a sound wave and shock wave that propagate at a certain speeds. A sound wave can change the state of the ceramic armour material before the projectile reaches it. The sound wave reflects from the fibre composite behind the ceramic armour element and returns in the form of a spherical wave in the direction opposite to the direction of the primary wave. Conditions are created for interference of the wave generated by the penetration of the bullet and the wave reflected from the back of the armour (composite fibre). Therefore periodic tensile and compressive stresses are generated by the bullet in the area not yet penetrated by it. The compressive stresses are particularly dangerous for ceramic plates because ceramics do not have a very high tensile strength and are characterised a high brittleness [37]. Importantly the ceramic structure destroyed after repeated firing ceases to fulfil its protective role with respect to the fibre composite, which under these conditions is exposed to much larger amounts of energy that can generate different mechanisms of absorption, e.g., deformation of fibres, fibre breaking from exceeding the breaking limit, shearing of fibres, delamination and cracking of fibres etc. In this study, damage to the ceramic armour was to be restricted to the area of the impact of the bullet, such that the waves acting on the material did not have time to spread. Thus the main cause of damage was local crossing of the strength limit at the front of the waves. Hybrid ceramic - multi-layered UHMWPE composite armour of this type required further testing to increase its protective efficiency. In order to improve the performance of ceramic armour systems by reducing the effect of shock wave reflection without a significant increase in their weight and thickness, a new system confinement of ceramic armour was proposed [38]. The tests focused on a selection of a suitable fibrous and polymeric materials that could constitute a system confinement for the front part of the ceramic armour to

Table 9. *Ballistic tests carried out using the multi-hit test procedure according to NATO STANAG 4569 [35] for hybrid ceramic - multi-layered UHMWPE composite armour based on hexagonal ceramic SiC with a thickness of 4.5 mm after conditioning at +50 °C and -40 °C.*

Parameter	Hybrid ceramic - multi-layered UHMWPE composite armour (used in conjunction with NIJ 0101.04/IIIA [34]; PN-V-87000:2011/K2/O3 [33] Vest)	Hybrid ceramic - multi-layered UHMWPE composite armour (used in conjunction with NIJ 0101.04/IIIA [34]; PN-V-87000:2011/K2/O3 [33] Vest) (containing the new system confinement)	
a	b	c	d
Conditioning temperature, °C	+50	+50	-40
Areal density, kg/m^2	22.7 ± 0.3	23.4 ± 0.3	23.3 ± 0.3
„multi-hit” according to NATO STANAG 4569 (AEP-55 Vol.1);7.62×51 FMJ			
Perforation	NO	NO	NO
Velocity, m/s	831	838	979
Deformation, mm	-	39	32
„multi-hit” according to NATO STANAG 4569 (AEP-55 Vol.1); 5,56×45 SS109			
Perforation	YES	YES	NO
Velocity, m/s	953	962	961
Deformation, mm	-	-	19
„multi-hit” according to NATO STANAG 4569 (AEP-55 Vol.1);7,62×39 PS			
Perforation	YES	NO	NO
Velocity, m/s	725	735	737
Deformation, mm	-	27	20

reduce the shock wave and weaken fragment displacement occurring. The system confinement consisted of three major components, as shown the ***Figure 6***:
- a technical textile mesh with an adhesive layer based on silane,
- p-aramid-phenolic prepreg (one-sided),
- foamed material with an adhesive layer.

For hybrid ceramic - multi-layered UHMWPE composite armour with the confinement system, firing was carried out using the ammunition indicated above (***Table 9***, columns c & d). Ballistic tests were performed on two sets in accordance with the multi-hit procedure for each of the following conditions:
- after conditioning at -40 °C,
- after conditioning at +50 °C.

Figure 7 shows the hybrid ceramic - multi-layered UHMWPE composite armour protected by the system confinement before and after impact (multi-hit test procedure/7.62 × 39 mm PS). In the case of multiple firing on the hybrid ceramic - multi-layered UHMWPE composite armour with the system confinement using 7.62 × 39 mm PS and 7.62 × 51 mm FMJ bullets, the ballistic strength desired was achieved, whereas for the composite system fired on with 5.56 × 45 mm SS109 bullets after conditioning at 50 °C, the ballistic strength assumed was not achieved, which associated with shooting through the system. To determine the extent of the damage on the hybrid ceramic - multi-layered UHMWPE composite armour, an X-ray examination was carried out followed by analysis with Imagine J, as shown in ***Figure 8***. Analysis of the area of damage after firing on the armour protected with and without the system confinement showed that in the case of unprotected armour, the damage area was approximately 25% greater compared to the armour protected with the system confinement. In the case of unprotected armour, the ceramic plates were torn form the fibre composite over a substantial area of the armour. In the case of protected armour, we observe only cracks in the plates and damage to a relatively small area of the armour, thereby making it possible to withstand another bullet. There are two possible explanations for this: damage to the hybrid ceramic - multi-layered UHMWPE composite armour with the system confinement absorbs more energy or the stress wave extending from the point of impact causes less damage due to the higher strength limits of the system confinement.

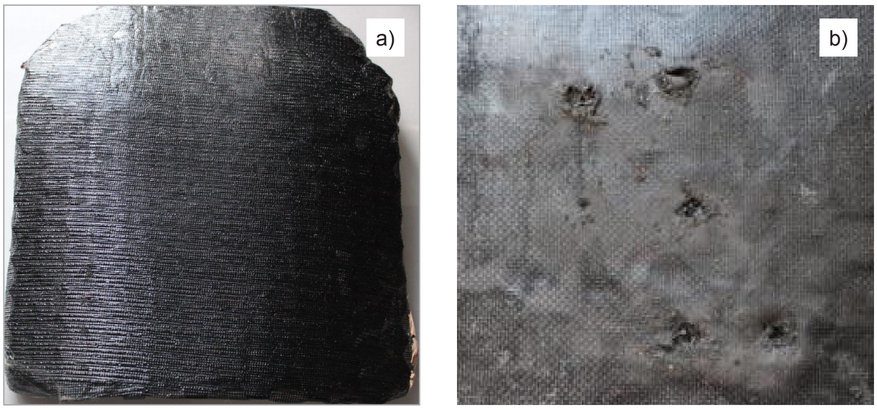

Figure 7. *Surface of hybrid ceramic - multi-layered UHMWPE composite armour with the system confinement layer: before ballistic tests (a), after ballistic tests using the multi-hit test procedure for 7.62 x39 mm PS bullets (b).*

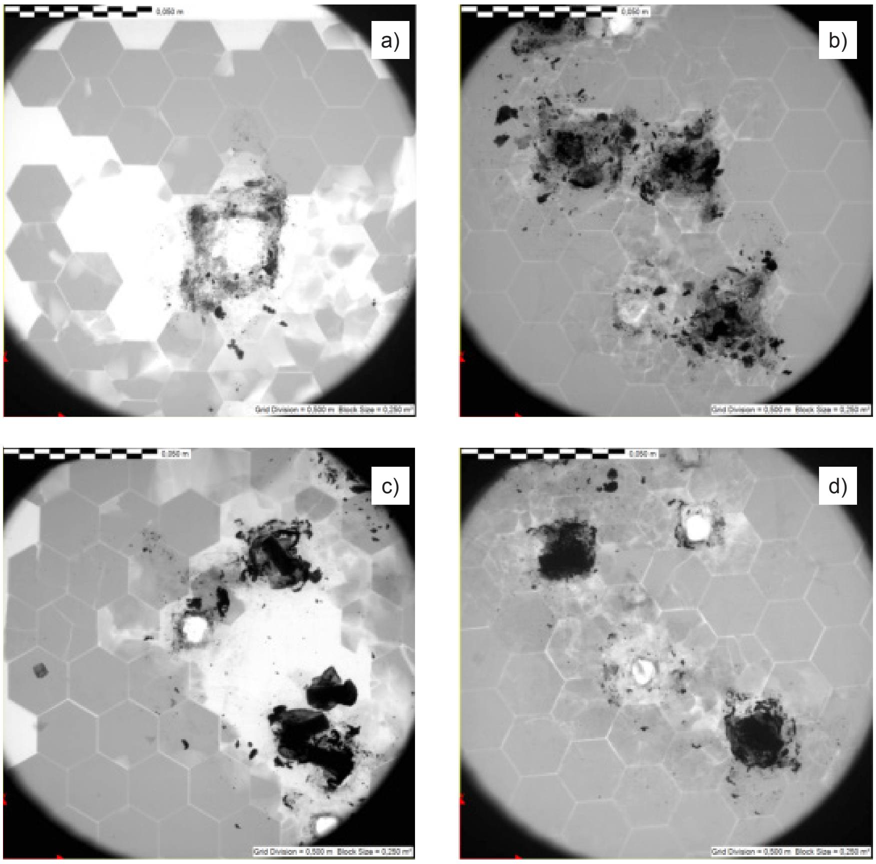

Figure 8. *RTR photos of unprotected hybrid ceramic - multi-layered UHMWPE composite armour (a), (c) and armour protected with the system confinement after ballistic testing (b), (d); a), b) multi hit/ 5.56×15 SS109; c), d) multihit/7.62×39 PS.*

Ballistic strength within the additional ballistic inserts based on cylindrical ceramics

Ballistic tests of hybrid ceramic - multi-layered UHMWPE composite armour based on cylindrical ceramics, introduced in ***Figure 9*** (see page 88), were conducted in accordance with the requirements of PN-V-87000:2011 [33]. The ballistic tests were carried out in "dry" conditions using a single impact with a 7.62 × 51 mm AP bullet for each sample. Results for the hybrid ceramic - multi-layered UHMWPE composite armour based on cylindrical ceramics after ballistic tests carried out in accordance with the requirements of PN-V-87000:2011 [33] are shown in ***Table 10*** (see page 88). For the hybrid ceramic - multi-layered UHMWPE composite armour, the test sample deflected by 36 mm and 41 mm

Figure 9. Hybrid ceramic - multi-layered UHMWPE composite armour based on cylindrical ceramic: sample without polyurethane (a), with polyurethane (b), after ballistic tests carried out in accordance with the requirements of PN-V-87000:2011 [33] using a single impact with a 7.62×51 mm AP bullet (c).

depending on the dimensions of the ceramic. The 17.27 mm thick hybrid ceramic - multi-layered UHMWPE composite armour did not meet the requirements of the standard because the depth of deformation of the material was higher than that assumed in PN-V-87000:2011 [33], i.e., a value of more than 40 mm. Therefore it did not display satisfactory ballistic strength after firing with 7.62 × 51 mm AP. The lower ballistic strength of this system was most likely due to the construction of the fibre composite material based on Dyneema®HB26 in the hybrid ceramic - multi-layered UHMWPE composite armour, which was characterised by low areal density in relation to the threat posed by the 7.62 × 51 mm AP bullets. The thickness of the ceramic armour should be selected according to the ballistic strength of the composite fibre component of the armour. The fibre composites play a very important role because the fibres directly under the bullet are subjected to high tensile stress. In these fibres, a longitudinal stress wave propagates at the speed of sound in the material, resulting in an associated deformation of the fibres. The fibre composite should block the bullet itself, as well as the shards of shattered ceramics, after piercing the armour. Improper selection of the fibre composite structure reduces the effectiveness of protection. The hybrid ceramic - multi-layered UHMWPE composite armour based on cylindrical ceramics provides an alternative to hybrid ceramic - multi-layered UHMWPE composite armour based on hexagonal ceramics, where the armour is a contoured 3D element and ballistic protection is required against high calibre bullets. Ballistic strength against high calibre bullets requires the use of ceramic elements in hybrid ceramic - multi-layered UHMWPE composite armour that have a considerable thickness, i.e., greater than 10 mm. It is difficult to arrange hexagonal ceramic plates with a thickness greater than 10 mm from the standpoint of the technological process. The use of cylindrical ceramics embedded in a suitable matrix polymer allows for versatile modelling of the shape of armour resistant to high calibre bullets.

Table 10. Results of ballistic strength tests of hybrid ceramic - multi-layered UHMWPE composite armour based on cylindrical ceramic.

No	Hybrid ceramic - multi-layered UHMWPE composite armour		Ammunition	Velocity, m/s	Deformation, mm	Perforation
	Multi-layered UHMWPE composite Areal density, kg/m^2	Ceramic SiC thickness, mm				
1	10	13.35	7.62×51 mm AP	857	36	NO
2	6	17.27		847	41 (not be up to standard)	NO

Conclusions

The aim of the research was to develop a new concept of hybrid ballistic materials consisting in ceramic and fibrous composite layers. The fibrous materials as well as the shape, thickness ceramics and system confinement were selected to take into accounta particular situation and ballistic requirements. Basic ballistic armour was developed using two types of polyethylene materials, Dyneema®SB21 and Dyneema®SB51, to simultaneously protect against three types of ammunition (7.62 TT FMJ, 9 mm FMJ, 44 Magnum SJHP) specified in two different standards: PN-V-87000:2011 and NIJ 0101.04, assuming a depth of deformation of the surface of less than 40 mm. In the basic ballistic armour, the system based on material made of polyethylene Dyneema®SB51 had the lowest areal density while maintaining the same level of ballistic strength as the armour made of Dyneema®SB21. A hybrid ceramic - multi-layered UHMWPE composite armour was developed on the basis of ceramics made of silicon carbide (SiC) and aluminium oxide (Al_2O_3) (of various shapes and sizes) with Dyneema®HB26. The hybrid ceramic - multi-layered UHMWPE composite armour based on hexagonal ceramics in combination with basic ballistic armour meets the requirements of resistance to firing with the following ammunition: 7.62×51 mm FMJ, 5.56×45 mm SS109, 7.62×39 mm PS, 4.6 mm×30 mm DM31 AP in the full range of test conditions (i.e., dry, after sprinkling, after conditioning at -40 °C and at +50 °C) according to PN-V-87000:2011. Ballistic tests of hybrid ceramic - multi-layered UHMWPE composite armour based on hexagonal ceramics also carried out in accordance with a multi-hit procedure modelled on NATO STANAG 4569 (AEP-55 Vol.1) showed that the area of cracks in ceramic plates was not limited to the plate immediately struck by the bullet. Damage (cracks or chipping, combined with detachment) was also apparent on the adjacent plates over a large area of the armour. Volumetric fracturing was assumed to be one of the causes of this type of damage. Armour damage caused by firing carried out in accordance with the multi-hit procedure significantly increased the scale of damage due to the short distances between impacts. It is possible to significantly reduce this phenomenon by using an appropriate system confinement of hexagonal ceramic plates connected permanently to the composite fibre. The system confinement [36] improves the protective efficiency of the ceramic armour by approximately 25% compared to armour without the system confinement. The hybrid ceramic - multi-layered UHMWPE composite armour with cylindrical silicon carbide ceramics has ballistic protection in accordance with PN-V-87000:2011 for 7.62 × 51 mm AP ammunition. The hybrid ceramic - multi-layered UHMWPE composite armour based on cylindrical ceramics showed that the thickness of the ceramic armour element should be selected according to the ballistic strength of composite fibre elements that are a part of the hybrid ceramic - multilayered UHMWPE composite armour. Depending on the requirements for ballistic protection, armour systems may be designed for various configurations and weights based on the most suitable materials. An appropriate material and system design are selected based on a particular situation and ballistic requirements. In this paper we introduced examples of successful designs of lightweight armour systems which may be useful for different ballistic requirements, including satisfactory multi-hit performance.

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