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Ballistic Helmet Development Using UHMWPE Fibrous Materials

Abstract
The main aim of the work was to develop a hybrid bullet- and fragment proof helmet protecting the user's head against small arm ammunition and fragments as well as mechanical impacts. In the construction of the shell, the latest generation of ballistic materials were used, developed on the basis of para-amide fabric coated with a thermosetting resin and high molecular weight polyethylene (UHMWPE). The idea of the study was based on the thesis that the stable connection of two types of fibrous materials differing in their structure, topography as well as in the type of the polymer (para-aramid and polyethylene) will increase the ballistic resistance as well as allow to reduce the mass of the final products. The results of research in the field of the screening of fibrous materials, the process of elaboration as well as the design of bullet- and fragment-proof hybrid helmets are also presented. The ballistic helmets designed were verified within the wide scope of requirements described in PN-V-87001:2011 as well as in the NIJ Standards.

Key words: *ballistic protection, ultra-high molecular weight polyethylene (UHMWPE), ballistic helmet, hybrid composite.*

Introduction

For over three decades, state-of-the-art ballistic helmets depended entirely on aramid fibres [1 - 4]. Currently work continues on the production of ballistic composites based on polyethylene fibres of ultra-high molecular weight (UHMWPE), polypropylene (PP) and carbon fibres [5 - 7]. The material properties for a ballistic helmet are standard, depending upon the helmet type.

The properties of selected materials used for helmets are given in ***Table 1*** [8]. Ultra high molecular weight polyethylene fibre was a very promising material for making light-weight high strength and high impact resistant composites, especially for ballistic head protection. Paper [5] shows that forming helmets of commercial high strength polyethylene fibre prepregs is possible. Commercial Dyneema® HB25 materials were used in the study. The Enhanced Combat Helmet (ECH), which has been under development since 2007 for the US Marine Corps and US Army, makes use of Dyneema® HB80 unidirectional composite material, which consists of a matrix of ultra-high molecular weight polyethylene (UHMWPE) reinforced by carbon fibres [6]. The weathering and gamma radiation effects on the ballistic properties of UHMWPE composite armour were studied by Alves et al. [8]. Composite plates were subjected to weathering (2 and 4 months) and gamma irradiation (25 kGy and 250 kGy). It was found that exposure to weathering for 4 months did not cause significant changes in ballistic impact resistance. However, it significantly increased delamination failures in the plate under a projectile impact, which was attributed to oxygen diffusion between the layers, reducing the interfacial resistance. Also it was observed that exposure to gamma radiation reduced the ballistic resistance. The higher the gamma radiation dosage, the larger the local damaged area. It was concluded that exposure to weathering and gamma radiation induces modification in the UHMWPE molecular structure, leading to changes in the mechanical and ballistic properties of the composite. It is therefore necessary to test the UHMWPE based helmet periodically to ensure that weathering and gamma radiation do not compromise the ballistic impact resistance of the helmet. It has become known that UHMWPE/carbon fibre composites can provide higher ballistic protection at a reduced weight than the composites used in current helmets. Polymer matrix nanocomposites, especially those reinforced by carbon nanotubes, can potentially offer the highest ballistic protection. However, their viability in terms of manufacturing

Table 1. *Properties of some materials for ballistic helmet designs used [7].*

Type of ballistic helmet	Material (shell/fabric)	Properties	Shell (matrix)	Fibre used (reinforcement)
Hadfield	Steel	Tensile strength, MPa	250	Not available
		Tensile modulus, GPa	183	
		Breaking strain, %	10	
PASGT	Thermoset resin/Kevlar K29 composite	Tensile strength, MPa	7386	2794
		Tensile modulus, GPa	195	67
		Breaking strain, %	3.8	3.5
ACH	Thermoset resin/Kevlar K129 composite	Tensile strength, MPa	7386	3429
		Tensile modulus, GPa	195	96
		Breaking strain, %	3.8	3.3
ECH	Dyneema® HB80 composite	Tensile strength, MPa	Not available	2500
		Tensile modulus, GPa		120
		Breaking strain, %		3.5 - 3.7

Table 2. Ballistic materials selected for fabrication of the hybrid ballistic helmet.

Material	Manufacturer	Areal density, g/m²
Dyneema® HB80 - composite materials of UHMWPE fibres	DSM High Performance Fibers BV (*The Netherlands*)	145 ± 5
Dyneema® HB26 - composite materials of UHMWPE fibres		260 ± 10
composite materials of polyethylene tapes Dynnema® BT10 (UHMWPE fibers)		470 ± 10
p-aramid-phenolic prepreg (one-sided) Twaron® CT736	Teijin Aramid (*The Netherlands*)	470 ± 30
p-aramid-phenolic prepreg (one-sided) Twaron® T750		530 ± 10
p-aramid-polyurethane prepreg BN-AA4 10B	BNS Industrial BV (*The Netherlands*)	530 ± 30
p-aramid-polyurethane prepreg BN-AA4 60P		370 ± 20
fabric of polypropylene tapes PURE® 251002	Lankhorst Pure Composites b.v. (*The Netherlands*)	100 ± 10

feasibility and cost effectiveness needs to be further explored [8]. The ballistic performance of helmets depends on the composite material properties, the type of fibres and matrix, the fibre orientation, the interaction between the fibres and matrix, as well as on the parameters of processing the composites dedicated for the helmet shell. In the literature [9] a process was disclosed for producing a hybrid helmet consisting in forming an outer layer of carbon fibre and polyethylene material as well as the application of polyester resin used to glue the outer layers to the inner layers of aramid. Patent specification [10] shows a protective helmet which is made from 17 layers of aramid fabric and 13 layers of polyethylene impregnated with a resin based on vinyl ester. The composition was pressed at a pressure of 190 tons and temperature of 121 °C for 15 minutes. In turn, U.S. Patent [11] presents a hybrid helmet constructed of composite materials which includes layers of aramid fabric and polyethylene. The fibrous materials used to produce the hybrid ballistic helmet were reinforced with a matrix of resins: phenolic, acrylic and polyester. The ballistic resistance of helmets depends on the properties of the composite material, the type of fibre and matrix, the orientation of fibres in the matrix, the interaction of the fibres with the matrix, and on the parameters of the process of manufacturing the composite materials [9 - 11]. It is important that the helmet be characterised by the lowest mass, while maintaining all aspects related to security and functionality; hence manufacturers in the design process tend to reduce the weight by using state-of-the-art construction and materials.

This paper presents the development of technologies for ballistic helmets made of aramid and polyethylene materials. The idea of the study was based on the thesis that the stable connection of two types of fibrous materials differing in their structure, topography as well as in type of polymer (para-aramid and polyethylene) will increase the ballistic resistance as well as allow to reduce the mass of the final products. Taking the above into account, the research was aimed at achieving a reduction in the mass of head ballistic protections while maintaining the ballistic protection level against bullets and fragments by the proper selection of materials, the selection of optimal conditions during the hybrid three-dimensional composite fabrication and finally by appropriate selection of the helmet design.

Materials

The criterion for the selection of materials to form the ballistic helmet was the maximum reduction in mass while maintaining aspects of its safety, functionality and reasonable cost. Based on an analysis of the availability of new materials to construct the hybrid ballistic helmet, the selection of appropriate fibrous materials was conducted (***Table 2***).

Methods

Research programme of modelling the ballistic resistance of composites dedicated for manufacturing hybrid helmets

The research programme of modelling the ballistic resistance of composites dedicated for manufacturing the hybrid ballistic helmet covered four stages:

1. Developing samples of single-layer flat ballistic composites of areal density of 5000.0 g/m² ± 100 g/m² and dimensions of 250.0 × 250.0 mm ± 0.2 mm (stage 1).
2. Developing samples of single-layer flat ballistic composites of equal ballistic performance V50 = 660 ± 10 m/s

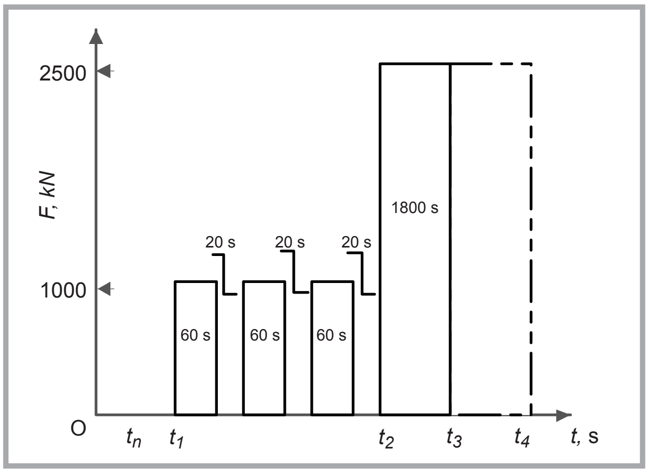

Figure 1. *Pressing process of the hybrid composite (p-aramid fibrous layer); t_n - warm-up time of package from a temperature of 120 °C to that of 170 °C; $t_1 – t_2$ - degassing time, $t_2 – t_3$ - main pressing time at temperature 170 °C, $t_3 – t_4$ - cooling time to temperature 80 °C.*

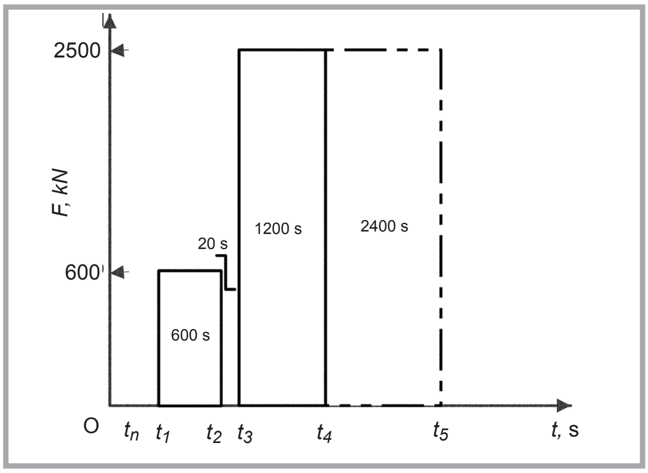

Figure 2. *Pressing process of hybrid composite (p-aramid fibrous layer connected with the UHMWPE fibrous layer); t_n - warm-up time of package to temperature 130 °C, $t_1 – t_2 – t_3$ - degassing time; ($t_1 – t_2$ - closed form, $t_2 – t_3$ - open form), $t_3 – t_4$ - main pressing time at temperature 130 °C;$t_4 – t_5$ - cooling time to temperature 65 °C.*

and dimensions of 250.0 × 250.0 ± 0.2 mm (stage 2).

3. Developing samples of two-layer flat ballistic composites of ballistic performance V50 = 660 ± 10 m/s and dimensions 250.0 × 250.0 ± 0.2 mm (stage 3).
4. Developing the hybrid ballistic helmet (stage 4).

Process of manufacturing

The technology of pressing many layers of fibrous ballistic materials was applied in the process of manufacturing the ballistic composites. The process of pressing unwoven polyethylene materials was performed in several stages and included the initial and main pressing at a temperature of 130 °C, and then cooling down to that of 70 °C. The pressing pressure was approx. 20 MPa. The process of pressing the aramid pre-impregnates was performed at a temperature of 160 – 170 °C, under a pressure of 10 – 30 MPa. The time of pressing and degasification applied in that case depended on the number of layers and kind of aramid pre-impregnate in the packet. In turn, the process of pressing the coated fabric of polypropylene ribbons included cooling the arrangement down to below 80 °C, main pressing at temperatures of 130 - 150 °C at a pressure of 10 MPa. The arrangement after the main pressing was cooled down to a temperature below 80 °C. In turn, the hybrid composite was pressed in a two-stage process, typical parameters of which are shown in ***Figures 1*** and ***2***.

The hybrid composite was made by the creation of an interlayer on the surface of the aramid composite as an alloy of one layer of the polyethylene material and phenolic resin modified with PVB which constitute a gluing layer in the aramid pre-impregnate. The layer of polyethylene textile structure has turned, at a temperature of 170 ºC, into film on the surface of the para-aramid composite, firmly joining with it. Due to the interlayer created, bonding the multiple-layer aramid structure with the polyethylene one at a temperature of 130 °C and pressure of 20 MPa was possible. Making the shell of the bullet- and fragment-proof helmet was conducted on the basis of the developed technology of pressing flat hybrid composite panels with the use of a hydropress with an oil heating system and two press moulds, varying in the gap between the punch and die [12].

Table 3. *Results of metrological and ballistic tests of the flat ballistic composites.*

Material	Thickness, mm	V50, m/s	Hardness, HBW
Dyneema® HB26	5.3 ± 0.01	611	9.8 ± 0.66
Dyneema® BT10	5.5 ± 0.01	510	14.4 ± 0.57
Kevlar FK N2	4.3 ± 0.01	467	6.9 ± 1.24
PURE 251002	7.0 ± 0.01	366	9.0 ± 0.75
Dyneema® HB80	5.2 ± 0.01	661	11.3 ± 1.34
Twaron® T750	4.3 ± 0.01	463	14.6 ± 1.30
Twaron® CT736	4.2 ± 0.01	469	13.4 ± 1.07
BN-AA4 60P	4.2 ± 0.01	454	8.8 ± 1.49
BN-AA4 10B	4.2 ± 0.01	450	7.6 ± 1.09

Analytical methods

Metrological assessment

The areal density and thickness of the flat ballistic composites were measured according to research procedure PBM – 33:2009 [13], compliant with standard [14], after conditioning defined in the PN-EN ISO 139:2006 standard [15]. Metrological assessment of the hybrid bullet- and fragment-proof helmet was made according to the PN-V-87001:2011 standard [16].

Assessment of ballistic properties

Tests of the ballistic resistance of the flat composites were executed according to methodology based on the NATO STANAG 2920:1996 standard [17] by finding the ballistic resistance limit - V50[1]. The test consisted in the assessment of the effective impact of standard fragments on the flat panel while the velocity of the hit is determined. The test was conducted at room temperature (20 ± 5 °C) and relative air humidity of (65 ± 10%). Each flat sample was shot at least six times: three resulting in partial penetration and three in full piercing. The result of each shot was evaluated by inspection of the sample tested. After the necessary number of shots the V50 velocity was calculated as the arithmetic mean of the three highest velocities of hits registered resulting in partial penetration and the three lowest velocities of hits registered resulting in full piercing, provided that the difference between those velocities did not exceed the value of 40 m/s.

Tests of the ballistic resistance of the hybrid ballistic helmet were executed for fragment-proofness expressed by the ballistic resistance limit V50 and bullet-proofness according to the PN-V-87001:1999 standard [18], as well as its new revision i.e. Standard PN-V-87001:2011 [16].

Regarding assessment of fragment-proofness according to the PN-V-87001:1999 standard [18], the deflection (Ug) of the hybrid ballistic helmet was measured after calculation of the V50 value, at a velocity of the standard fragment of V = 0.9 × V50, whereas for assessment of the fragment-proofness V50 according to PN-V-87001:2011 [16], the deflection of helmet was measured at the standard fragment velocity of V = 540 ± 15 m/s (class O3).

Moreover the bullet-proofness was assessed according to the requirements of the following Standards:

- NIJ Standard 0108.01 [19],
- NIJ Standard 0106.01 [20],
  - level II (9 mm Parabellum FMJ 8 g bullet of the hit velocity of 358 ± 15 m/s),
  - level IIIA (9 mm Parabellum FMJ 8 g bullet of the hit velocity of 426 ± 15 m/s, compliant with the NIJ standard 0108.01) [20].

Tests of ballistic resistance were executed at a temperature of -40 °C and +50 °C, at which the ballistic resistance should not change compared to the value obtained for products not exposed to the impact of -40 °C and +50 °C temperatures. During tests of the bullet-proofness of the helmet according to item 5.2 of NIJ Standard 0106.01, the capability of the helmet to attenuate the energy when hit with a bullet was obtained.

Assessment of the mechanical properties

Tests of the hardness of the flat composites and the hybrid, bullet- and fragment-proof helmet were executed based on the PN-EN ISO 2039-1:2004 standard [21]. A ball of 5 mm diameter was used as the penetrator and the measurement load was 613 N [22]. Tests of three-point bending were executed with the use of an INSTRON testing machine, and a force within the range up to 200 kN according

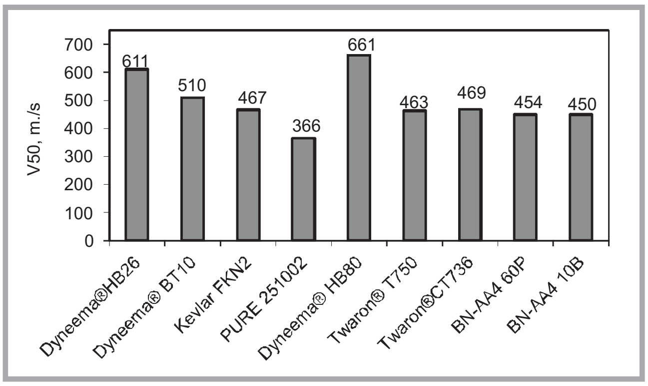

Figure 3. Assessment of the V50 ballistic protection of the flat ballistic composite.

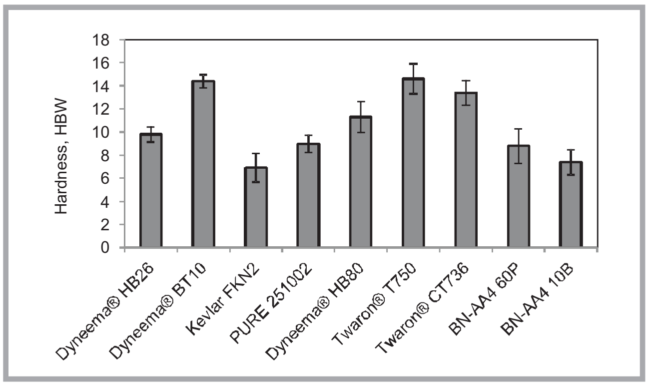

Figure 4. Assessment of the hardness of the flat ballistic composite.

to methodology based on the PN-EN ISO 178:2011 standard [23].

Results of the test and discussion

Assessment of the ballistic properties flat composites

The basic criterion for selecting materials in the process of developing the hybrid ballistic helmet were the ballistic and mechanical properties of ballistic flat composites made of them. The research programme elaborated allowed to indicate two of eight materials (***Table 2***), and a target ballistic hybrid helmet was made of them. Considering the research programme, samples of the ballistic composites of an areal density of 5000.0 ± 100 g/m^2 and dimensions of 250.0 × 250.0 ± 0.2 mm were realised in stage 1. Flat composite panels were subjected to metrological, ballistic and mechanical tests, the results of which are listed in ***Table 3*** (see page 91). Based on the results of tests of the ballistic resistance V50 (***Figure 3***) and hardness of composite flat panels (***Figure 4***), as well as considering the areal density of materials used to make them, two materials were indicated for further tests (stage 2): unwoven polyethylene material Dyneema® HB80 and Twaron® CT736 pre-impregnate. The samples made of those materials in the first stage proved to have the highest value of V50 as well as some of the highest values of hardness. Moreover the materials used for manufacture had the lowest values of areal density. For further optimisation of the composite dedicated for the shell of the ballistic helmet, samples of flat composites were made of the materials mentioned above (Dyneema® HB80, Twaron® CT736) with dimensions of 250.0 × 250.0 ± 0.2 mm and with the lowest possible areal density, while keeping the ballistic resistance at V50 = 660 ± 10 m/s. ***Figure 5*** shows the results of testing the ballistic resistance V50 of the flat composites developed at stage 2.

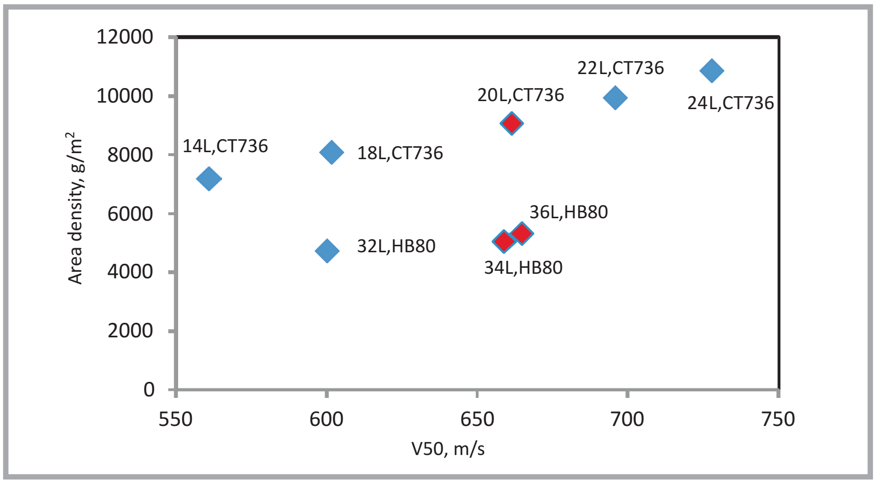

Figure 5. Relationship between the ballistic resistance (V50) and areal density of the flat composite made of Dyneema® HB80 or Twaron® CT736 materials; L – number of fibrous layers, HB80 - Dyneema® HB80 fibrous composite material, CT736 - Twaron® CT 736 prepregnate of woven fabric.

The tests of samples of the flat composites (stage 2) indicated that a ballistic resistance V50 within the range of V50 = 660 ± 10 m/s was achieved by the composite made of 20 layers of Twaron® CT736, or that made of 34 - 36 layers of Dyneema® HB80. The goal of further studies was to reduce the mass of a composite dedicated for the manufacture of a hybrid ballistic helmet, with consequent improvement of its ergonomics while keeping a ballistic resistance of V50 = 660 ± 10 m/s. In relation to that, a technology was developed and hybrid flat two-layer composite panels were made of two materials (Dyneema® HB80, Twaron® CT736). The values of ballistic resistance V50 and the areal densities of the hybrid flat composite panels are listed in ***Table 4***.

Tests of the flat composites of hybrid structure indicated that the composite featured a diversified ballistic resistance limit V50, within the range from 589 m/s to 663 m/s. The lowest value of ballistic resistance V50 was found for the flat hybrid composite built of 14 layers of Twaron® CT736 and 6 layers of Dyneema® HB80, whereas the highest values of ballistic resistance V50 were found for the sample made of 16 layers of Twaron® CT736 and 6 layers of Dyneema® HB80. The value of V50 of the hybrid materials tested exceeded or was close to the presumed V50 = 660 ± 10 m/s. The technology of manufacturing coherent flat hybrid composite panels developed allowed to develop guidelines for making moulds for the technology process adopted – pressing many layers of aramid-phenolic pre-impregnate (Twaron® CT736) and unwoven polyethylene material (Dyneema® HB80).

Bullet- and fragment-proof hybrid helmet

Analysis of ballistic properties

After material optimisation of the hybrid composite in the form of flat samples, structures were developed and patterns of materials made based on unwoven polyethylene material Dyneema® HB80 and Twaron® CT736 pre-impregnate in order to construct a hybrid helmet of the target design (***Figure 6***). When shaping the shell, the patterns were placed one on another so that the gash of each layer was shifted from those of adjacent layers, with the width of no gash exceeding 2 mm. The number of layers of the material was the same in each cross section of the helmet shell. In order to verify the developed structure of the hybrid composite based on unwoven polyethylene product Dyneema® HB80 and pre-impregnate of para-aramid fibres and phenolic resin modified with PVB (Twaron® CT736), the ballistic resistance expressed by the V50 and deflection Ug of hybrid shells of the helmets was tested according to the PN-V-87001:1999 standard. The ballistic resistance V50 depended remarkably on the percentage share of Dyneema® HB80 material in the structure of the shell. When comparing the ballistic parameters of hybrid shells consisting of various amounts of Dyneema® HB80 and Twaron® CT736 a remarkable improvement in V50 was observed along with an increase in the Dyneema® HB80 share in the helmet shell (***Figure 7***, see page 94). In addition to the tests of V50, the deflection of the hybrid ballistic helmet was assessed according to PN-V-87001:1999, measured after calculation of V50 at a velocity of a standard fragment of V = 0.9 × V50.

Table 4. *Results of metrological and ballistic tests of the flat hybrid ballistic composites.*

Sample	Hybrid system made of	V50, m/s	Number of layers in system	Overall thickness, mm	Areal density, g/m²
1	Twaron® CT736	589	14	6.2 ± 0.01	7100 ± 100
	Dyneema® HB 80		6		
2	Twaron® CT 736	599	14	6.1 ± 0.01	6100 ± 100
	Dyneema® HB 80		6		
3	Twaron® CT736	663	16	6.8 ± 0.01	8000 ± 100
	Dyneema® HB80		6		
4	Twaron® CT736	631	14	7.8 ± 0.01	6900 ± 100
	Dyneema® HB80		10		
5	Twaron® CT736	629	14	7.7 ± 0.01	6900 ± 100
	Dyneema® HB80		9		
6	Twaron® CT736	628	12	7.2 ± 0.01	6800 ± 100
	Dyneema® HB80		14		
7	Twaron® CT736	627	13	7.6± 0.01	7000 ± 100
	Dyneema® HB80		12		

Table 5. *Results of tests of the ballistic resistance (V50) and deflection (Ug) of s hybrid ballistic helmet of optimum design (Tests according to the PN-V-87001:1999 standard).*

Conditions of testing	V50, m/s	Ug, mm
normal conditions	710	20
normal conditions	708	20
temperature -40°C	716	20
temperature +50°C	698	19

Table 6. *Results of resistance tests of the hybrid ballistic helmet of optimum design to shooting with 9 mm Parabellum FMJ 8.0 g bullets, at a hit velocity of Vu = 345 + 15 m/s and deflection (Ug) according to the PN-V-87001:1999 standard; Vu –bullet velocity measured at hit, FMJ – Full Metal Jacket.*

Conditions of testing	9 mm Parabellum FMJ		
	Vu, m/s	Ug, mm	Location of shot
normal conditions	354	32	front
	357	29	side
	355	32	back
normal conditions	359	32	front
	352	30	side
	356	32	back

When analysing the deflections of the helmets, an increase was observed along with an increase in V50 (***Figure 7***). Considering the study above, the structure of the hybrid helmet was optimised so as to gain the highest possible V50 parameter while maintaining the lowest possible values of deflection.

Figure 6. *Photographic documentation depicting the steps of ballistic hybrid helmet fabrication.*

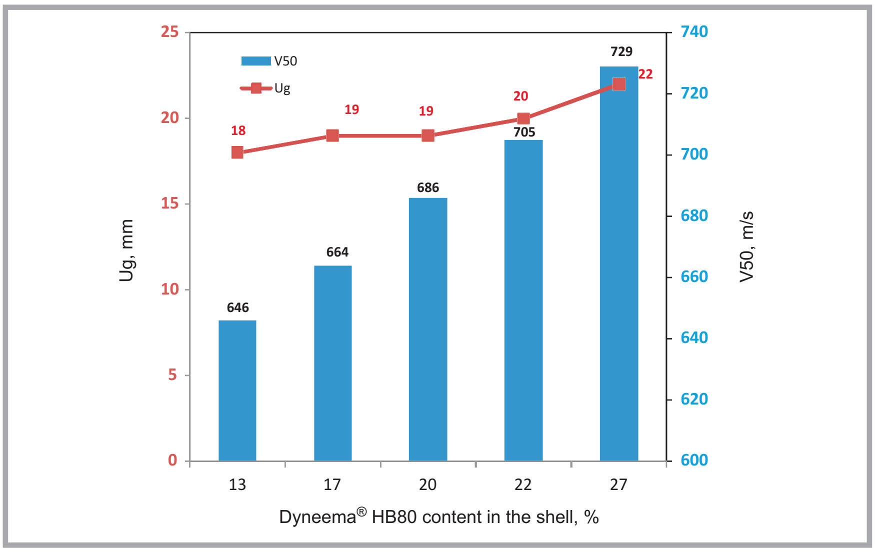

Figure 7. *Effect of the % content of Dyneema® HB80 in % in the shell of the hybrid ballistic helmet on V50 and Ug.*

Table 7. *Results of tests of the ballistic resistance (V50) and deflection (Ug) of the hybrid ballistic helmet of optimum design (Tests according to the PN-V-87001:2011 standard).*

Conditions of testing	V50, m/s	Ug, mm
normal conditions	723	16
temperature -40°C	714	15
temperature +50°C	750	15

The final design of the hybrid ballistic helmet developed consisting of an 80% share of Twaron® CT 736 preimpregnate and 20% share of unwoven polyethylene material Dyneema® HB80 was tested for ballistic resistance according to the following standards: PN-V-87001:1999, PN-V-87001:2011, NIJ Standard-0106.01, and NIJ Standard-0108.01.

At the first stage of the studies, assessment was made of the ballistic resistance expressed by V50 and the resistance to shooting with 9 mm Parabellum FMJ bullets (mass m = 8.0 g, velocity V = 345 + 15 m/s) of the ballistic hybrid helmet according to the PN-V-87001:1999 standard. The results are listed in ***Tables 5*** and ***6***.

Tests of the hybrid ballistic helmet at room temperature and at -40 °C and +50 °C proved that it satisfies the requirements of the PN-V-87001:1999 standard concerning fragment-proofness. The helmet also exhibits ballistic resistance to shooting with 9 mm Parabellum FMJ bullets (mass m = 8.0 g, velocity V = 345 + 15 m/s) at room temperature according to the PN-V-87001:1999 standard.

Subsequently the ballistic resistance limit V50 and deflection Ug were assessed according the PN-V-87001:2011 standard (***Figure 7***).

Studies on the hybrid ballistic helmet showed that it meets the requirements of the PN-V-87001:2011 standard concerning fragment-proofness at room temperature as well as at temperatures of -40 °C and +50 °C.

Furthermore the following parameters were also assessed:

1. bullet-proofness of hybrid ballistic helmets according to the requirements of the PN-V-87001:2011 standard (***Table 8***),
2. bullet-proofness of hybrid ballistic helmets to the projectiles compliant to level IIIA according to NIJ Standard-0108.01 (***Table 9***),
3. bullet-proofness according to the requirements of NIJ Standard-0106.01 (***Table 10***):
   - level II (9 mm Parabellum FMJ, 8 g bullet at a hit velocity of 358 ± 15 m/s),
   - level IIIA (9 mm Parabellum FMJ, 8 g bullet at a hit velocity of 426 ± 15 m/s).

During research on the bullet-proofness of the helmets, their capability to attenuate the energy when hit by a projectile was also assessed. Tests were performed according to section 5.3 of NIJ Standard-0106.01. The capability of the hybrid ballistic helmet to attenuate energy characterised by the value of acceleration is shown in ***Table 11***. The highest acceleration was transferred to the model of

Table 8. *Results of resistance tests of the hybrid ballistic helmet of optimum design to shooting with 9 mm Parabellum FMJ 8.0 g bullets, at a hit velocity of Vu = 345 + 15 m/s and with 357 Magnum JSP 10.2 g bullets at a hit velocity of V = 425 ± 15 m/s) according to the PN-V-87001:2011 standard; JSP – Jacketed Soft Point.*

Conditions of testing	9 mm Parabellum FMJ			357 Magnum JSP		
	Vu, m/s	Location of shot	Perforation, yes/no	Vu, m/s	Location of shot	Perforation, yes/no
normal conditions	357	front	no	430	front	no
	362	back		435	back	
	360	side 1		427	side 1	
	364	side 2		427	side 2	
temperature +50°C	352	front		445	front	
	364	back		429	back	
	366	side 1		446	side 1	
	361	side 2		424	side 2	
temperature -40°C	367	front		436	front	
	368	back		441	back	
	364	side 1		432	side 1	
	360	side 2		435	side 2	

Table 9. Results of resistance tests of the hybrid ballistic helmet of optimum design to shooting with 9 mm Parabellum FMJ 8.0 g bullets at a hit velocity of V = 426 ± 15 m/s and a 44 Magnum Lead SWC 15.55 g bullet at a hit velocity of V = 426 ± 15 m/s); LSWC – Lead Semi Wad Cutter.

Conditions of testing	9 mm Parabellum FMJ			44 Magnum LSWC		
	Vu, m/s	Location of shot	Perforation, yes/no	Vu, m/s	Location of shot	Perforation, yes/no
normal conditions	428	front	no	418	front	no
	427	back		421	back	
	431	side 1		426	side 1	
	435	side 2		430	side 2	
temperature +50°C	426	front		432	front	
	429	back		430	back	
	435	side 1		435	side 1	
	437	side 2		419	side 2	
temperature -40°C	420	front		425	front	
	425	back		436	back	
	430	side 1		428	side 1	
	422	side 2		420	side 2	

Table 10. Results of resistance tests of the hybrid ballistic helmet of optimum design to shooting with 9 mm Parabellum FMJ 8.0 g bullets at a hit velocity of V = 358 ± 15 m/s and 9 mm Parabellum FMJ 8.0 g bullets at a hit velocity of V = 426 ± 15 m/s.

Conditions of testing	9 Para FMJ/II			9 Para FMJ/IIIA		
	Vu, m/s	Location of shot	Perforation, yes/no	Vu, m/s	Location of shot	Perforation, yes/no
normal conditions	365	front	no	428	front	no
	359	back		425	back	
	361	side 1		427	side 1	
	362	side 2		430	side 2	
soaking in water	358	front		416	front	
	357	back		428	back	
	362	side 1		428	side 1	
	361	side 2		428	side 2	
normal conditions	365	front		421	front	
	359	back		423	back	
	362	side 1		425	side 1	
	357	side 2		421	side 2	

Table 11. Results of energy attenuation capability tests of the hybrid ballistic helmet of optimum design when shot with 9 mm Parabellum FMJ 8.0 g bullets at a hit velocity of V = 358 ± 15 m/s and 9 mm Parabellum FMJ 8.0 g bullets at a hit velocity of V = 426 ± 15 m/s.

Conditions of testing	9 Para FMJ/II				9 Para FMJ/IIIA			
	Vu, m/s	Location of shot	Perforation, yes/no	Maximum acceleration transferred to head model (gn)	Vu, m/s	Location of shot	Perforation, yes/no	Maximum acceleration transferred to head model (gn)
normal conditions	365	front	no	260	421	front	no	265
	359	back		30	423	back		97
	362	left side		31	425	left side		50
	357	right side		75	421	right side		108

a head when shot in the front and right side of the helmet, which was where the helmet proved to have lowest capability to attenuate energy. Such a result was confirmed when it was shot with 9 mm Parabellum FMJ bullets, both at a hit velocity of 358 ± 15 m/s and 426 ± 15 m/s. In order to compare the ballistic properties of the hybrid ballistic helmets developed to aramid ones, helmets based on the aramid composite were made by replacing the polyethylene patterns with aramid ones. The number of aramid patterns was chosen in a manner so that their areal density was the equivalent of that of polyethylene patterns included in the composition of the hybrid helmets' shell. The aramid helmets and hybrid helmets developed were subjected to tests of fragment-proofness according to the PN-V 87001:1999 standard (***Table 12***). Analysis of the research on the ballistic resistance of hybrid and aramid helmets, expressed by V50, indicated that the newly developed helmets compared to the aramid ones, but featuring a higher ballistic resistance V50 and lower values of deflection while keeping the mass at the same level.

Analysis of mechanical properties

The hybrid ballistic helmet developed was subjected to assessment of the hard-

Table 12. Results of ballistic resistance (V50) and deformation (Ug) of hybrid and aramid ballistic helmets.

Type of helmet	Shell mass, g	V50, m/s	Ug, mm
hybrid	935 ± 5	686	19
aramid		668	24
hybrid	945 ± 5	664	19
aramid		668	22
hybrid	1020 ± 5	705	20
aramid		691	21

Table 13. Results of metrological research of the hybrid ballistic helmet.

Parameter	Type/Value
Helmet mass	≤ 1450 g (Depending on inside equipment)
Shell mass	≤ 1140 g
Protection surface	1140 cm^2
Helmet dimensions (medium)	length (A) = 268 ± 3 mm width (B) = 254 ± 3 mm height (C) = 170 ± 3 mm
Clearance	≥ 10 mm
Resistance of the outer shell of the helmet	In accordance with the requirements of point 4.9 of PN-V-87001:2011, (no damage to the outer shell of the helmet)
Water resistance	mass gain of helmet after exposure to water is < 1% of the initial weight thereof

ness and bending strength. Within the present study the values of these parameters were determined with the use of four helmets, the results of which are representative of any hybrid ballistic helmet. Analysis of the results of mechanical research showed that the hardness of the ballistic helmet developed at its inner surface (aramid part) is 13 - 17 HBW, whereas at the outer surface (polyethylene part) it is 11 - 15 HBW [22]. The hardness values gained for the helmet shell on its aramid and polyethylene parts are at a level comparable to that gained for flat composite samples made of Dyneema® HB80 and Twaron® CT736 (***Figure 4***). The results of research on hardness confirm that the technology process of manufacturing ballistic hybrid helmets was properly developed. On the other hand research on the bending strength indicates that this parameter is significantly dependant on the location within the helmet where a sample for testing was taken from. The bending strength of the hybrid ballistic helmet was, respectively, for:

- right side – 215 MPa
- left side – 169 MPa
- back – 150 MPa
- front – 198 MPa

Explanation of the findings above must be related to various values of the pressing force of the press occurring in the moulds during the process of pressing, thereby affecting the changes in UHMWPE particles as well as the aramid-phenolic pre-impregnate. Thus the bending strength of the front and right side of the helmet increases, as supposed, because of greater values of the press down-force in those areas of the mould, which translates into better bending strength of the front and right-side parts of the helmet. Comparison of the bending strength of the hybrid ballistic helmets and their capability to attenuate the energy when hit with a projectile (tests compliant with section 5.3 of NIJ Standard 0106.01) seems interesting. The highest acceleration transferred to the head model, and therefore the lowest capability to attenuate the energy, occurs in frontal or right-side shooting, with the highest values of bending strength also being at the front and right side of the helmet. A clear trend appears which shows that the higher the bending strength, the lower the capability of helmet to attenuate the energy. It was important to optimise the conditions of the technology process to provide the helmet with the best bending strength, which translates to its mechanical strength, while maintaining the highest possible level of the capability of the helmet to attenuate energy. The results of mechanical tests of the hybrid ballistic helmet considering the optimum variant shall be the basis for a quality check of a batch of hybrid helmets manufactured on an industrial scale.

Analysis of metrological research

Metrological research of the hybrid ballistic helmet was performed according to test procedure [24] based on Standard [16]. The tests consisted in verifying the following properties:

1. the overall dimensions, mass of the shell and that of the complete helmet,
2. protective area of helmet,
3. clearance space,
4. resistance of the outer coat of the helmet,
5. resistance to the action of water.

Results of the research are listed in ***Table 13***. The mass of the shell of the hybrid ballistic helmet developed was ca. 1140 g and the protective area was 1140 cm^2. Applying the material composition based on aramid-phenolic pre-impregnate (Twaron® CT736) and unwoven polyethylene material (Dyneema® HB80) to the structure of the helmet allowed for an average reduction in the finished product's mass of 20%, compared tothat made of the homogenous aramid composite. At the same time, it allowed for a reduction in the material cost of the product developed compared to the helmet made of more expensive homogenous material, which was UHMWPE, while keeping the same level of ballistic resistance in every case [25]. The research also confirmed that the helmet has proven resistance to the action of water. The increase in the helmet mass after 16 hours of soaking in water at a temperature of 15 - 20 °C was no bigger than 1% of the helmet's initial mass. The external coat of the hybrid ballistic helmet was resistant to dropping from a height of 2 m onto a concrete ground; no damage consisting in a loss of coating continuity appeared. The results of metrological research obtained confirmed the compliance of the parameters tested with the PN-V 87001:2011 standard.

Conclusions

The new hybrid ballistic helmet developed protects a wearer's head against the projectiles of small-callible firearms and against fragments and mechanical blows from the line of the brow to the top, on the side of the ear behind the occipital bone, and from the back of the the occiput to the top of the head. Based on the research performed it was confirmed that the helmet provides ballistic resistance defined by class K2 according to the PN-V-87001:2011 standard and by level IIIA according to NIJ Standard 0108.01. Moreover the hybrid ballistic helmet satisfies the requirements of NIJ Standard 0106.01 concerning bullet-proofness:

- level II (9 mm Parabellum FMJ 8 g bullet at a hit velocity of V = 358 ± 15 m/s),
- level IIIA (9 mm Parabellum FMJ 8 g bullet at a hit velocity of V = 426 ± 15 m/s, according to NIJ Standard 0108.01).

The design of the hybrid helmet incorporates an innovative solution where the hybrid composite aimed to provide the product with usage properties of a higher level than those of helmets previously in use among units operating within the field of internal security. To make the new helmet, the latest generation ballistic materials were used and a composite developed consisting of a pre-impregnate made of CT 736 fabric of para-aramid Twaron® fibres and phenolic resin modified with PVB (one-sided prepreg) and ultra-high molecular weight polyethylene (UHMWPE). Application of such a kind of material arrangement to the structure of the helmet allowed to develop a product featuring higher ballistic resistance V50 and lower values of deflection compared to that made of a single-sided aramid composite, while keeping the masses of the aramid and hybrid helmets at the same level. Moreover such a material solution allows to reduce the material costs of the product developed, compared to the helmet made of more expensive homogenous material: the UHMWPE.

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Editorial note

[1] *V50 – ballistic resistance limit (velocity of the projectile at which the probability of piercing the material is 50%)*

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