

Development of Flexible and Lightweight Ballistic Body Armor

Constructional Contributions for Ballistic Components out of Ultra-High-Molecular-Weight Polyethylene

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Abstract—In the last years, the risk to become a victim of a gun fight or to be involved into an amok situation increased. This leads to a higher demand for ballistic protection of civilians. Therefore, another capability profile for ballistic armor is necessary, compared to the military or police sector. The focal point of civil ballistic armor is wearing comfort, weight and invisibility. This paper provides information about the development of flexible and lightweight ballistic body armor. The manufacturing process is showed, heat- and sag test are presented, and first ballistic trials will be discussed below. The aim of the project is to create a ballistic body armor, which is flexible, and body fit enough to be worn under a sweater or suit. Furthermore, the body armor should meet the fourth level of ballistic protection of the "Association of test laboratories for bullet resistant materials and constructions" (VPAM 4). The idea can be realized by using an ultra-high molecular weight polyethylene (UHMWPE) composite. A material with well-balanced properties to fulfill the ballistic and mechanical requirements.

Keywords - defense engineering; ballistic body armor; armor systems; fiber-reinforced plastics; ballistic trials; material processing.

I. INTRODUCTION

Personal integrity is a basic need. Nowadays, this need is endangered by increased incidents relating to gun violence. Especially in the USA, the number of incidents rises from about 50,000 to over 60,000 between 2014 and 2017 [1]. This leads to a higher need for personal ballistic protection at the civilian markets. Included are products like soft-ballistic sweater inlays or discrete ballistic vest, which are suitable for everyday life. In this area of use weight, wearing comfort and invisibility are focal points. The ballistic protection up to the fourth level of ballistic protection of the "Association of test laboratories for bullet resistant materials and constructions" (VPAM 4) has to be ensured. These requirements make it necessary to use a material, which combines high tensile strength for a high ballistic performance and low density for a suitable weight balance. These attributes are combined in many fiber reinforced composite materials, especially ultra-high molecular weight polyethylene (UHMWPE) is well suited for the mentioned application. Already existing analyses of the ballistic behavior of UHMWPE, like in [2] or [3] described, are often on a theoretical level. This paper aims

for an analysis on an applied level, with a concrete connection to a product development. Existing theoretical results are applied to the development of an actual ballistic vest. This leads to the overall aim of the project to create a flexible and lightweight ballistic vest, which meet the VPAM 4 regulations and can be worn under everyday clothes. Therefore, the project is divided into five sections:

1. Material processing (Section IV);
2. Material pre-testing (Section V);
3. Pre-ballistic testing (Section VI);
4. Ballistic testing (future work);
5. Finalization (future work).

This paper aims to provide data to derive a decision about the material composition, which is used for the future work.

The paper is structured as follows. In Section II, preliminary considerations are introduced regarding material, processing and shape of the test objects. Section III gives a brief information about the used UHMWPE prepreg material and the second matrix material. Section IV is about the processing of ballistic plates namely cutting and lamination process. In Section V, heat resistance test and sag test are presented and discussed. In Section VI, the pre-ballistic test, which includes VPAM 3 (third level of ballistic protection of the "Association of test laboratories for bullet resistant materials and constructions") and VPAM 4 testing, is described and evaluated. The final section, Section VII, merge all results and, these results are discussed, leading to the constructive design of the plates.

II. PRELIMINARY CONSIDERATIONS

In the beginning of the project two questions occur:

- Which material is suitable for the project (ballistic performance and weight)?
- How can it be processed to become a flexible ballistic plate?

First thoughts about the material leads to the UHMWPE in detail Dyneema® HB26. This material, in shape of hard-ballistic-plates, was successfully tested in previous ballistic trails. The plates were made out of multiple layer of pre-impregnated fiber (prepreg) material, which are fused under a certain pressure and temperature to become a solid ballistic plate. These ballistic trails have already been reported in [3].

This type of Dyneema® HB26 plates have an inflexible structure, making them unsuitable for this project of soft-ballistic-plates. On the other hand, the material shows a good ratio between weight and ballistic performance. In detail, areal density of the material is between 257 – 271 g/m² [3] and has an energy absorption per areal density of ~35 J·m²/kg [3]. In Section IIIA the mechanical properties of the material are explained in detail to enhance the awareness for the material.

Relating to the second initial question, Dyneema® HB26 provides a promising starting point, because this basic prepreg already offers a flexible structure. Therefore, the prepreg material only needs a second flexible matrix material to hold the prepreg layers together. Due to this, a lamination process by hand is selected, which makes it possible to use a flexible cast resin. This leads to the question, which kind of cast resin has to be used as a second matrix material. It has to be considered, that, firstly, the cast resin does not destroy the chemical basic structure of the prepreg material and secondly, the cast resin remains flexible. To ensure this chemical compatibility of the second matrix material the same matrix material, like it is used for the prepreg, is chosen. For that reason, a polyurethane (PUR) determines the second matrix material. This is selected out of the group of thermoplastic elastomers (TPE) [4]. Under the aspect of flexibility, a cast resin out of PUR with special flexible properties is chosen. A further description of the second matrix material is given in Section IIIB.

Beside the material, also the shape of the plates is important for the ballistic performance. This is, because of the anisotropic properties, which are described in Section IIIA. In this case, the shape was predetermined, because the plates have to fit into already existing structures.

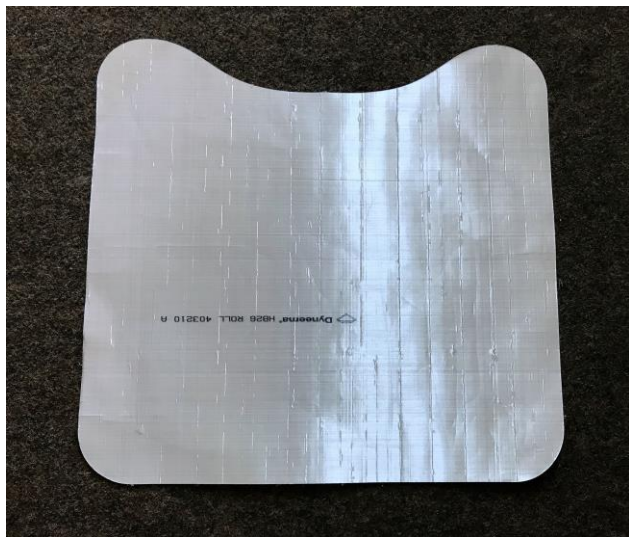


Figure 1. Main body pattern out of Dyneema® HB26. Width of 435 mm and a total height of 415 mm.



Figure 2. Side body pattern out of Dyneema® HB26. Width of 150 mm and a total height of 205 mm.

Relating to the standard size of a plate carrier inlay, plates were produced in a size of 300 mm x 250 mm. Furthermore, patterns for a sweatshirt inlay were used to evaluate the behavior of the different shapes in a ballistic trail. The main body pattern has a width of 435 mm and a total height of 415 mm (Figure 1). The side body pattern is narrower and has a width of 150 mm and a height of 205 mm (Figure 2).

III. USED MATERIALS

The basic material for the development of the flexible plates is Dyneema® HB26. It is shipped in a shape of a tape and as such, the matrix and fiber have already combined to a prepreg. The fiber is out of UHMWPE and the matrix out of PUR. As mentioned in Section II, the second matrix material is a flexible PUR.

A. Dyneema® HB26

The prepreg material consists of four sublayers of UHMWPE fibers, which are bidirectional orientated. The fiber direction per sublayer is turned by 90°, compared with the previous layer. This achieves an equal force dissipation in the prepreg material. Resulting from this structure, different geometric shapes of the material have anisotropic tensile properties, because of unequal fiber length.

The prepreg material has a density of 0.97 g/cm³. UHMWPE fibers have a high molecular weight. Commonly they have an Intrinsic Viscosity (IV) from 8 IV up to 30 IV. The fiber achieves high tensile strength (between 3.21 GPa and 5.99 GPa) and initial modulus (between 113 GPa and 171 GPa) through long molecular chains out of methylene groups (CH₂). A characteristic of UHMWPE is, that the intra molecular bounds are relative weak Van der Waals bounds. Though, the extreme long molecule chains leading to a significant overlap between the molecule chains. This results in many inter molecular Van der Waals bounds, which strengthen the overall intermolecular stability. Further developments have to consider, that the fiber length is one of the most important constructional attributes, because of the link to the tensile strength of the material [5].

The matrix material of the prepreg has multiple tasks. Firstly, to protect the fiber against environmental conditions,

pressure and kinks. Secondly, to hold the fibers in their position and direction. Finally, the matrix leads the forces into the fibers. Matrix material is often chosen from the group of thermoplastic elastomers, because of moldability and high elongation at break. These are good properties to support the fibers and the construction.

B. Cast Resin System - Second Matrix Material

The most important requirement for second matrix material is to preserve the flexibility of the prepreg. Therefore, the second matrix material has also to be flexible. As mentioned in Section II, the flexible PUR called R15GB-flex was selected. This material is a two-components cast resin system, consisting out of resin and hardener. With a mixing ratio of 100 parts resin and 25 parts hardener a Shore hardness (A) of ~40 is achievable. Compared with normal PUR cast resin systems, which have a Shore hardness (D) of ~65 (comparable to a Shore hardness (A) of ~105), the used PUR has a softer texture [6]. Another important property is the density of the second matrix material to keep a low overall weight. The material R15GB-flex has a density of 1.1 g/cm³, comparable with the density of the prepreg material. The material has in mixed condition a medium viscosity and a processing time of approximately 15 min (100 g at 20 °C). These properties make the material suitable for the lamination process by hand. The maximum usage temperature is around 50 °C [5]. This fact will further be discussed in Section V.

IV. PROCESSING

The processing of the ballistic plates is divided into two stages:

- Cutting process for semi-finished parts;
- Lamination process for the finished composite material.

A. Cutting Process

This project stage needs two patterns. First of all, the standard plate carrier inlay with rectangular, plane shape and dimensions of 300 mm x 250 mm. For the testing procedures one 5-layer, two 10-layer, one 15-layer and two 20-layer plates are produced (Table 1). Overall, 80 layers of prepreg material in this shape are necessary.

Furthermore, patterns for a sweatshirt inlay, with a main body part (Figure 1) and side part (Figure 2) are used. On the whole, 30 main body part layers and 15 side part layers are produced (Table I).

The lamination process by hand makes it necessary to laminate every single layer. In this particular case, a fast-laser-cutting-process is unsuitable, because the individual layers would melt together. A single layer cut with the laser cutter is as well inefficient, due to the rectangular shape. For that reason, every layer has to be cut out by a special scissor for reinforced fibers.

To achieve a high precision, the more complex shapes of the sweatshirt patterns are cut by the laser. The patterns are replicated in a computer-aided design (CAD) program and saved as drawing exchange format (DXF) file. Lastly, the file is exported into the laser cutter program and executed

(parameters: Power 120 W, frequency 1000 Hz, velocity 0.036 m/s). Due to the four-sublayer structure of the prepreg material, a homogeneous sublayer structure is achievable even without rotation between the prepreg layers.

B. Lamination Process

The hand lamination process requires following stages:

- Mixing;
- Coating;
- Hardening process.

In the mixing process, the mixing ratio is adjusted by the proportion of weight. For a low Shore hardness (A) the manufacturer recommends a mixing ratio of 100 parts resin and 25 parts hardener. Proportion of weight of the two components, which is necessary for the different plate sizes, are shown in Table II. The two components are mixed with a wooden stick to a homogenous mixture.

This mixture is equal spread over the prepreg layer with a lamination brush. For the coating, a slight film is sufficient. Pressure from the inside to the outside is applied to get a compact compound.

Finally, surplus material is removed, and the plates are laid into a warm place for 24 h for hardening. After the hardening process, the plates are inherently stable.

V. HEAT AND SAG TEST

Besides the ballistic performance, further two primary material attributes of the new composite material have to be tested. Firstly, the heat stability in a heat test, because of possible high surface temperatures in area of use. Secondly, the flexibility of the material, as key functionality in a sag test.

A. Heat Test

Heat is a weak point of the second matrix material, due to its thermoplastic properties. Maximum temperature of usage is around 50 °C according to the manufacturer. Analyses of the possible area of use show, that the average temperatures are moderate temperatures between 10 °C and 30 °C, which are unproblematic for the composite material. Nevertheless, in desert areas, which are possible areas of use, surface temperatures can reach a maximum around 70 °C and daily surface temperatures around 60 °C [7]. To test the heat resistance of the composite material, one plate is faced a heat test.

TABLE I. PROPORTION OF WEIGHT OF RESIN AND HARDENER FOR DIFFERENT AMOUNT OF LAYERS

Layer	Resin [g]	Hardener [g]	Final Thickness [mm]
5	42.6	11.55	2
10	85.2	23.1	4.2
15	127.8	34.65	6.8
20	170.4	6.2	9.3

TABLE II. OVERVIEW OF THE CONSTRUCTED TEST OBJECTS

Plate Number	Test Number	Layers	Thickness [mm]	Weight [g]	Shape	Processing Method
1	1	10	4	295.8	Rectangular	Lamination
2	2	10	4.2	295.9	Rectangular	Lamination
3	3	15	6.8	448.3	Rectangular	Lamination
4	4	20	9.2	614.8	Rectangular	Lamination
5	5M	20	9	592.6	Rectangular	Lamination
	5R					
6	/	5	2	159	Rectangular	Lamination
7	7	15	10	/	Side Part	Loose
8	8	10	6.4	/	Main Body Part	Loose
9	9	20	13.3	/	Main Body Part	Loose

The heat test proceeds as follows: an oven is preheated to a temperature of 30 °C. This 30 °C stage is used as a reference result. Every 30 min the temperature is set to a new value, first 50 °C, then 60 °C and finally 70 °C. The plate is left in the oven for 30 min. After 15 min and 30 min the plate is taken out and checked regarding: degeneration, flexibility, slip of layers and defects. A 5-layer plate (Plate No. 6) is chosen to ensure an even temperature distribution in material. Results are displayed in Table III.

The results show that the composite material, and especially the second matrix material withstand temperatures up to 50 °C without any property changes. At higher temperatures above 50 °C an increased flexibility is recognizable. After 30 min at 70 °C the layers of prepreg are movable 3 mm against each other. After this movement, the layers go back to their initial state. At all temperature stages the plate shows no degeneration and defects. Following a cooling phase, the second matrix material solidified again. Summing up, the higher temperatures are uncritical to the composite material.

TABLE III. RESULTS OF THE HEAT TEST

Temperature [°C]	Time [min]	Degeneration	Flexibility	Slip of Layers [mm]	Defects
30	15	Non	Unchanged	Non	Non
	30	Non	Unchanged	Non	Non
50	15	Non	Unchanged	Non	Non
	30	Non	Unchanged	Non	Non
60	15	Non	Slightly increased	Non	Non
	30	Non	Slightly increased	Non	Non
70	15	Non	Increased	>1	Non
	30	Non	Increased	3	Non

B. Sag Test

Flexibility is a key attribute of the used type of ballistic protection. Comparative values of the plate flexibility can be generated through a sag test. The aim of this test is to measure the sag of the plate under a certain load.

Therefore, a test procedure is created. The test setup is shown in Figure 3. The plates are laid onto two bars with a contact area of 10 mm x 250 mm on both sides. Moreover, the basic test setup consists of two rulers and a wooden baseplate (35 mm x 145mm), which are arranged as in Figure 3 shown. The sag test was conducted at 22 °C.

As a result of this arrangement, a basic load of 72.8 g lays up on the plate. Additionally, a 500 g block is used as a test weight. The center of the wooden baseplate is positioned in the middle of the plate at 150 mm x 125 mm. One ruler is placed for measurements and the other as an indicator for it. The zero height is 120 mm.

First, the initial height of the plate is measured. In this phase the plate has an additional load of 72.8 g. After 30 sec under these conditions, the height is measured.



Figure 3. Sag test basic test setup with test weight.

TABLE IV. RESULTS OF THE SAG TEST

Plate Number	Initial Height [mm]	End Height [mm]	Delta (Sag) [mm]
1	131	165	34
2	143	183	40
3	129	153	24
4	123	128	5
5	125	128	3

Subsequently, the plate is loaded with test weight. After 10 sec under these conditions, the height is measured again. Results are displayed in Table IV. The results show that 20-layer plates have deficits in their sag values and thus in the overall flexibility. They may be too inflexible for this particular application area. The 15-layer plate has a good ratio between number of layers and flexibility, compared with the 10-layer plate.

VI. BALLISTIC TEST

The ballistic test is performed on the basis of the VPAM ("Association of test laboratories for bullet resistant materials and constructions") regulations. Especially following regulations are regarded: general basis for ballistic material, construction and product testing (APR) [8], ballistic protective vests (BSW) [9] and bullet resistant plate materials (PM) [10].

The aim of this project is to meet the regulations of VPAM 4. This level requires, that the plate withstand a penetration of a .357 Mag. fired with a projectile velocity of 430 ± 10 m/s from 5 m distance [8]. A ballistic placement test provides an overview of the ballistic performance of the composite material. Therefore, a modified VPAM 3 (9 mm, 415 ± 10 m/s, 5m) and VPAM 4 level is tested. The shooting distance is increased to 10 m. Penetration and back face deformation are evaluated. Based on VPAM BSW No. 4.2 a maximal transmitted energy of 70 J is acceptable.

A. Preparation and Test Setup

Two components are necessary for the test setup: shooting-box and plasticine (Figure 4). The shooting box is built in consideration of the VPAM BSW [9]. The inner dimensions of the shooting-box are 300 mm width, 250 mm height and 150 mm depth. Especially the characteristic depth is important, because of compression effects with the rear panel. Based on the VPAM PM contact areas of 30 mm on three sides are built in [9]. The used plasticine is recommended by VPAM (VPAM BSW No. 5.2) [9]. The ballistic test is conducted at an ambient temperature of 21 °C.

A measurement of the plasticity is conducted as described in VPAM BSW No. 5.2.1. The mean imprint depth (d_m) of the plasticine is 19.8 mm. With this value and the maximal transmitted energy (E_{max}) of 70 J, the maximal volume (V_{max}) of the back-face deformation is calculated as follows [8]:

$$V_{max} = (0.134 \cdot d_m - 1.13) \cdot E_{max} \quad (1)$$

$$V_{max} = (0.134 \cdot 19.8 - 1.13) \cdot 70 = 106.624 \quad (2)$$



Figure 4. Shooting-box filled with plasticine. Inner dimensions: 250 mm x 300 mm x 15 mm.



Figure 5. Left side: .357 Mag 158 Gr. Right side: 9 mm Luger 124 Gr.

This leads to a maximal back face deformation volume of 106.624 cm^3 .

The gun, which is used for VPAM 3 testing is a SIG Sauer X-Five® with a 9 mm Luger 124 Gr. projectile. For the VPAM 4 testing an S&W 686 European Match® with a .357 Mag 158 Gr. projectile is used (Figure 5).

All shots are fired into the middle of the plates. The only exception is test number 5R, which get shot into the edge area. This edge shot has to hit the material in a distance of 30 ± 5 mm from an edge [9]. Test number 8 and 9 were shot without the shooting-box to check the penetration level of the loose layers.

B. Evaluation

After every shot the diameter and the depth of the imprint of the back-face deformation is measured (Table V). With these values, and the volume equation of a circular cone the volume of the back-face deformation (V) is calculated. Additionally, the transmitted energy (E) is calculated backwards with following equation [8]:

$$E = V / (0.134 \cdot d_m - 1.13). \quad (3)$$

TABLE V. RESULTS OF THE BALLISTIC TEST

Test Number	Layers	Caliber	Imprint -			Transmitted Energy [J]	Comments
			Depth [mm]	Diameter [mm]	Volume [cm ³]		
1	10	9 mm	34.4	8.0	57.638	37.840	/
2	10	.357	/	/	/	/	Penetration
3	15	9 mm	26.0	7.0	33.353	21.897	/
4	20	.357	29.8	9.0	63.193	41.487	/
5M	20	9 mm	18.3	5.0	11.977	7.863	/
5R	20	9 mm	/	/	/	/	Leaving material
7	15	9 mm	40.4	7.0	51.698	33.940	/
8	10	9 mm	/	/	/	/	Stuck in fourth layer
9	20	.357	/	/	/	/	Stuck in fourth layer

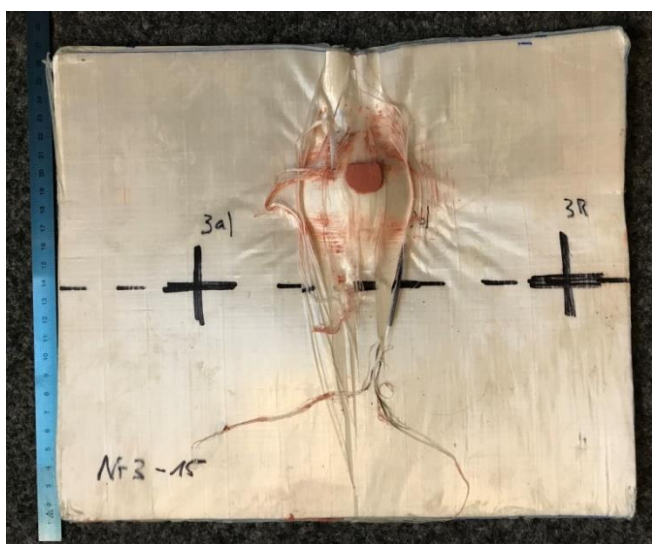


Figure 6. Test number 3 after the shot. Seeable is the back-face deformation and material behavior.

The results show, that test number 1, 3, 4, 5M, and 7 meet the requirement, that the transmitted energy is lower than 70 J. Especially test number three (15 layers) (Figure 6) shows a good average transmitted energy, comparing to test number 1 (10-layers) and 5M (20 layers).

Test number 5R failed, because the projectile left the plate before it gets stuck in the plate. As expected, test number 2 got penetrated by the .357 Mag projectile. This test was conducted to see the penetration behavior of the material and projectile, like layer and projectile movement, deformation of the projectile and damage to the plate. At test number 8 and nine the projectile got stuck in the fourth layer of the loose layers. The back-face deformation of these test numbers is negligible.

VII. DISCUSSION

The heat-resistance-test shows, that the composite plates are durable up to 70 °C. At higher temperatures a slip of layers is highly possible. Up to 60 °C no degeneration or melting is detectable (Table III). Thus, the second matrix

material and main material are suitable for the estimated conditions.

To examine the flexibility, a sag test is conducted. It shows, that 20-layer plates are too stiff for this area of use. 10- and 15-layers plates show good values of flexibility and weight compared to other soft ballistic plates (Table IV).

The ballistic plate has to meet the requirements of VPAM 3 and VPAM 4. This requirement allows a maximal transmitted energy of 70 J. In a first placement test all expected plates meet this requirement by far (Table V). Also, the sweatshirt inlays were tested successfully. It seems, that the extensive shape, which leads to longer fibers, increases the ballistic performance.

To summarize, the 15-layer plate is the best performing plate, because of the ratio between flexibility, weight and ballistic performance. 10-layer plates will not meet the VPAM 4 regulations, and 20-layer plates are too stiff and heavy for the area of use. These results will put the 15-layer plate into the focus of the studies. It has to be considered, that these ballistic results are from a pre-testing series. They are just indicators for a relative rating between our ballistic plates. In further ballistic tests they have to be verified for the VPAM 4 level.

VIII. CONCLUSION AND FUTURE WORK

All in all, the aim of this project is to create lightweight and flexible ballistic body armor for the civilian market. Therefore, a UHMWPE prepreg as main material and a two-component flexible resin as second matrix material is used. Through a lamination by hand procedure, ballistic composite plates are produced. Because of this method, the flexible properties of the main material are sustained. Moreover, a temperature resistance of the composite material up to 60 °C is identified. All conducted experiments show, that the 15-layer plate full fill our expectations best. Especially, the ballistic results of this plate are promising. Furthermore, compared to other available products on the market, the new plate has a reduced weight of ~100 g, is 1.2 mm slimmer and full flexible.

In further scientific work, the 15-layer plate will be extensive ballistic tested. Especially, VPAM 4 testing will

be focused. Greater effort will be spent into ballistic testing of the sweatshirt patterns and analyses of size-effects. Therefore, these special shaped plates will be also produced with the lamination process by hand and ballistic tested. Furthermore, new available prepreg material out of UHMWPE, special made for flexible ballistic plates, will be tested within following projects.

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