Development of Flexible and Lightweight Ballistic Body Armor

Comparative Ballistic Studies on Different Ultra-High-Molecular-Weight Polyethylene Materials

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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. Different ultra-high molecular weight polyethylene (UHMWPE) composites, in this case made by Dyneema®, are compared by using ballistic tests and will be discussed below. In this test series Dyneema® hard ballistic (HB) 26, HB50 and soft ballistic (SB) 115 is used. 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) as well as the requirements of the VPAM ballistic protection vests (BSW). The idea can be realized by using an UHMWPE composite. A material with well-balanced properties to fulfill the ballistic and mechanical requirements, simultaneously providing the necessary wearing comfort.**

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

I. Introduction

Based on the findings in [1] this article provides further ballistic trials. These trails are evaluated and first series relevant findings are achieved.

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 [2]. 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 [3] or [4] 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 (Section VII);
5. Finalization (future work).

This paper aims to provide data to derive a decision about the material composition, which is used for the finalization. The decision should be especially based on the results of the ballistic testing, mentioned in Section VII.

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 different used UHMWPE prepreg materials 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. Section VII is about the ballistic test. It includes the basic testing of the newly used materials and further, a comparative ballistic test to show the differences (in contrast) to the pre-ballistic test. The final section, Section VIII, merges 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 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 [4].

This type of 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 [5] and has an energy absorption per areal density of ~35 J·m²/kg [5].

Nowadays, newer materials are available, like the improved Dyneema® HB50 or the Dyneema® SB115. The HB50 is an enhanced HB26. The basic design is consistent, but the areal density is lower (226 – 240 g/m²) and the ballistic properties of the material have to be checked and compared in Section VII [6]. SB115 is a prepreg material, consisting of UHMWPE fibers. This material is especially produced for flexible and lightweight body armor applications, due to the very low areal density (75 – 84 g/m²) and notably flexible matrix material [7]. In Section III the mechanical properties of these materials 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) [5]. 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 IIID.

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. 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) [1].

III. USED MATERIALS

The basic material for the development of the flexible plates is UHMWPE prepreg material. A prepreg material is fiber composite material where the fibers are already combined with the matrix material. Various numbers of sublayers are implemented into a prepreg.

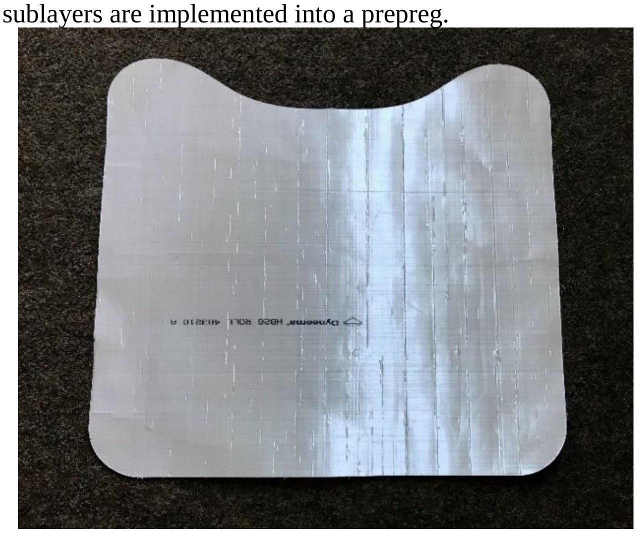

Figure 1. Main body pattern out of Dyneema® HB26. Width of 435 mm and a total height of 415 mm.

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

In this case Dyneema® HB26, HB50 and SB115 is used as a main material. As mentioned in Section II, the second matrix material is a flexible PUR.

A. *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 fibers are out of UHMWPE and the matrix out of PUR. 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 approximately 0.85 g/cm³, due to a martial thickness of 0.3mm. 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 113GPa and 171 GPa) through long molecular chains out of methylene groups (CH_2). 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 [8].

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 [1].

B. Dyneema® HB50

This UHMWPE material is an improved HB26 with the same basic physics. Also, the mechanical properties, especially the tensile strength (between 3.21 GPa and 5.99 GPa) and initial modulus (between 113GPa and 171 GPa), are the in same range as HB26. Section VII shows that these two mechanical properties of HB50 are (slightly) better than those of HB26, due to the improved ballistic results. It is quite possible that the tensile strength and initial modulus of HB50 is located in the upper area of the mentioned range. With 0.753 g/cm^3 HB50 has also a lower density compared to HB26 [6].

C. Dyneema® SB115

Dyneema® SB 115 is also a UHMWPE based fiber reinforced composite material. It is specially designed for soft armor applications, due to its flexible and soft matrix material and low areal density of 75 – 84 g/m^2. The prepreg material consist of two sublayers which are bidirectional orientated (0°, 90°), thus it is a cross ply. Additionally, the whole prepreg is covered with a coating, to protect the prepreg material against environmental damages, like chemicals and water [7]. Overall, one layer of the material has a thickness of 0.2 mm. This leads to a density of approximately 0.375 g/cm^3. The SB 115 consists of the fiber SK99. This fiber has a tensile stretch of 3.5 % and a tensile strength of 3.92 GPa. This high strength is based on the so called "Dyneema® Force Multiplier Technology" [9].

D. 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 [10]. 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/cm^3, 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 [8]. This fact will further be discussed in Section V [1].

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.

This will only be presented in detail for the plates, which were constructed for pre-tests and pre-ballistic test (Table I). The processing procedure for the plates used in the ballistic test are the same and can be abstracted. An overview of these plates is given in Table II.

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 I). 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 [1].

B. Lamination Process

The hand lamination process requires following stages:

- Mixing;
- Coating;
- Hardening process.

TABLE I. OVERVIEW OF THE CONSTRUCTED TEST OBJECTS FOR THE PRE-TEST AND PRE- BALLISTIC TEST

Plate Number	Test Number	Material	Layers	Thickness [mm]	Weight [g]	Shape	Processing Method
1	1	Dyneema® HB26	10	4	295.8	Rectangular	Lamination
2	2	Dyneema® HB26	10	4.2	295.9	Rectangular	Lamination
3	3	Dyneema® HB26	15	6.8	448.3	Rectangular	Lamination
4	4	Dyneema® HB26	20	9.2	614.8	Rectangular	Lamination
5	5M 5R	Dyneema® HB26	20	9	592.6	Rectangular	Lamination
6	/	Dyneema® HB26	5	2	159	Rectangular	Lamination
7	7	Dyneema® HB26	15	10	/	Side Part	Loose
8	8	Dyneema® HB26	10	6.4	/	Main Body Part	Loose
9	9	Dyneema® HB26	20	13.3	/	Main Body Part	Loose

TABLE II. OVERVIEW OF THE CONSTRUCTED TEST OBJECTS FOR THE BALLISTIC TEST

Plate Number	Test Number	Material	Layers	Thickness [mm]	Weight [g]	Shape	Processing Method
12	12M 12L 12R	Dyneema® HB50	15	6.5	395.6	Main Body Part	Loose
13	3M 13L 13R	Dyneema® SB115	15	4.1	197.8	Main Body Part	Loose

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 of hardener. Proportion of weight of the two components, which is necessary for the different plate sizes, are shown in Table III. 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.

TABLE III. 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

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 [1].

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.

Because of the nearly equal mechanical properties of HB26 and HB50, these tests were skipped for HB50 and will be done in future work. Based on the ballistic results, these tests will not be conducted for SB115.

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 [11]. To test the heat resistance of the composite material, one plate is faced a heat test.

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 IV.

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 [1].

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.

TABLE IV. RESULTS OF THE HEAT TEST

Tempe-rature [°C]	Time [min]	Degene-ration	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

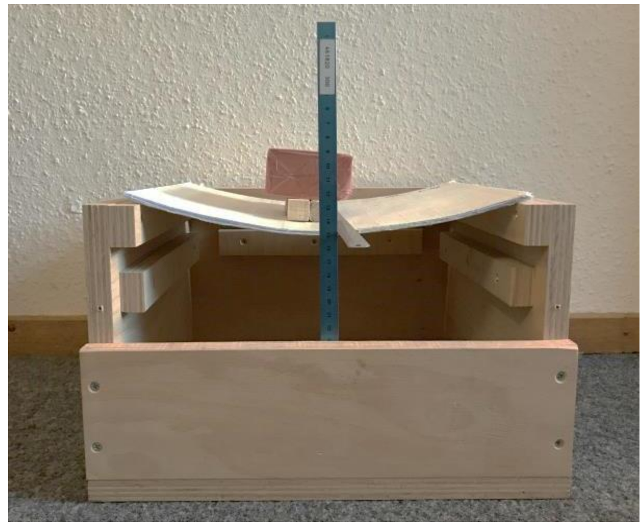

Figure 3. Sag test basic test setup with test weight.

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.

Subsequently, the plate is loaded with test weight. After 10 sec under these conditions, the height is measured again. Results are displayed in Table V. 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 [1].

VI. PRE-BALLISTIC TEST

The pre-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) [12], ballistic protective vests (BSW) [13] and bullet resistant plate materials (PM) [14].

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 [12]. 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.

TABLE V. 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

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 [13].

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 [13]. 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 [14]. The used plasticine is recommended by VPAM (VPAM BSW No. 5.2) [13]. 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 shown in (1) [12].

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

Using the values of the mean imprint (19.8 mm) and maximal transmitted energy (70 J) in (1) leads to (2).

$$V_{max} = (0.134 \cdot 19.8 - 1.13) \cdot 70 = 106 \quad (2)$$

This leads to a maximal back-face deformation volume of 106 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).

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.

All shots are fired into the middle of the plates. The only exception is test number B5R, 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 [13]. Test number B8 and B9 were shot without the shooting-box to check the penetration level of the loose layers [1].

B. Evaluation

After every shot the diameter (d) and the depth of the imprint (t) of the back-face deformation is measured (Table VI). With these values, and the volume equation of a circular cone the volume of the back-face deformation (V) is calculated (3).

$$V = \frac{1}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^2 \cdot t \quad (3)$$

Additionally, the transmitted energy (E) is calculated backwards with following equation [8]:

$$E = V / (0.134 \cdot d_m - 1.13). \quad (4)$$

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). Figure 7 shows the back-face-deformation in the clay after shot three. The deformation is wider and not as deep as in the other tests. This is a good result, because deeper back-face-deformation can more likely lead to internal injuries. For that reason, a flatter and wider imprint is strived. Test number 5R failed, because the projectile left the plate before it gets stuck in the plate. As expected, test number 2 got perforated 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 [1].

TABLE VI. RESULTS OF THE BALLISTIC TEST PHASE 1

Test Number	Layers	Caliber	Imprint -			Transmitted Energy [J]	Comments
			Depth [mm]	*Diameter [mm]*	*Volume [cm³]*		
1	10	9 mm	34.4	80	57	37.840	/
2	10	.357	/	/	/	/	Perforation
3	15	9 mm	26.0	70	33	21.897	/
4	20	.357	29.8	90	63	41.487	/
5M	20	9 mm	18.3	50	11	7.863	/
5R	20	9 mm	/	/	/	/	Leaving material
7	15	9 mm	40.4	70	51	33.940	/
8	10	9 mm	/	/	/	/	Stuck in fourth layer
9	20	.357	/	/	/	/	Stuck in fourth layer

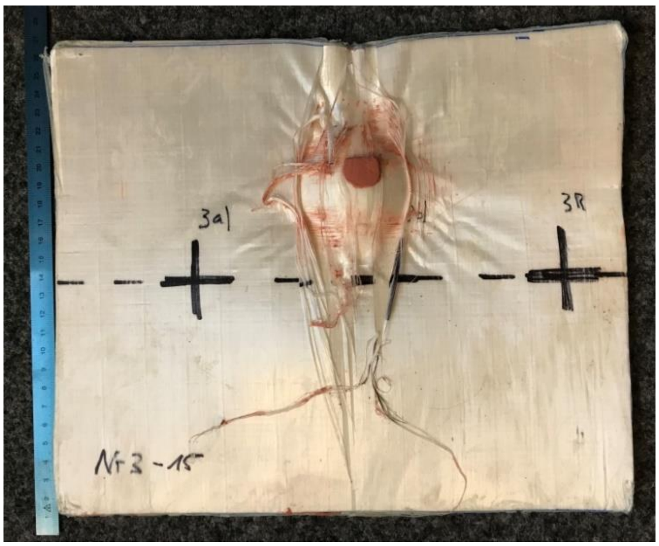

Figure 6. Test number 3 after the shot. Seeable is the back-face deformation and material behavior.

Figure 7. Test number 3 after the shot. Seeable is the volume of the back-face deformation in the clay.

VII. BALLISTIC TEST

The ballistic test is performed on the base of the VPAM APR [12] and VPAM BSW [13]. The aim of this test is to verify the shirt patterns for VPAM 3. This level is chosen, because there were no initial experiences with these materials. VPAM 3 requires that the plate withstand a penetration of a 9 mm Luger fired with a projectile velocity of 415 ± 10 m/s from 5 m distance [12]. Additionally, based on VPAM BSW, it has to withstand two additional shoots with a spacing of 75 mm arranged like an equilateral triangle [13].

A. Preparation and Test Setup

To get an idea of the back-face deformation while using the shirt patterns, a new test set up was constructed (Figure 8). This is necessary, because they do not fit into the shooting box, which was used in the pre-ballistic test. This time it is constructed completely based on VPAM BSW 5.1. The inner dimensions of the shooting-box are 400 mm width, 350 mm high and 150 mm depth. The shirt patterns are fix with Velcro fastener to the shooting-box. The used plasticine is recommended by VPAM (VPAM BSW No. 5.2) [13]. The ballistic test is conducted at an ambient temperature of 19 °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 20.2 mm. Equation (1) is used to calculated the admitted maximal back-face deformation volume.

Figure 8. Test number 12M after the first shot. Seeable is the principle test setup, based on VPAM BSW.

$$V_{max} = (0.134 \cdot 20.2\ - 1.13) \cdot 70 = 110.376 \quad (5)$$

This leads to a maximal back-face deformation volume of 110.376 cm^3.

The gun, which is used, is a H&K® MP5 with a 9 mm Luger 124 Gr. projectile. The velocities are measured with a light barrier measurement system. The average projectile velocity is 410.7 m/s, thus in the allowed range of the VPAM APR. The first shoot is fired into the middle of the of the plate (12M, 13M). The second shot is fired onto the left side of the first shoot, with a spacing of 75 mm (12L, 13L). The third shot is fired onto the right side of the second shoot, with a spacing of 75 mm, to get an equilateral triangle (12R, 13R).

B. Evaluation

After every shoot depth and diameter of the imprint is measured. With these values, the volume of the imprint with (3) and then the transmitted energy with (4) is calculated. The results are displayed in Table VII.

The results show that all shoots of test number 12 and the first shoot of test number 13 (13M) meet the requirements of VPAM BSW, because the transmitted energy is lower than 70 J. At test numbers 13R and 13L the projectile perforated the material, thus they do not meet the requirements of VPAM BSW. The front and the back side of test number 12 is shown in Figure 9, test number 13 in Figure 10. In the penetration process the kinetic energy of the projectile is partially dissipated into the deformation of the projectile (Figure 11). A flat deformed projectile shows an acceptable energy dissipation duo to the mechanical properties of the fiber. A nearly intact projectile shows that the fibers absorb none of the projectile energy.

TABLE VII. RESULTS OF THE BALLISTIC TEST

Test Number	Imprint -			Transmitted Energy [J]	Comments
	Depth [mm]	*Diameter [mm]*	*Volume [cm³]*		
12M	45.88	71	60	38.09	Stuck in ninth layer
12L	35.54	63	36	23.42	Stuck in ninth layer
12R	37.27	68	45	28.61	Stuck in ninth layer
13M	32.2	62	32	20.55	Stuck in fifth layer
13L	/	/	/	/	Perforation
13R	/	/	/	/	Perforation

Figure 9. Left side: the frontside of test number 12. Right side: the backside after the shooting. Readable on the backside is the stuck layer, back-face deformation depth and projectile velocity.

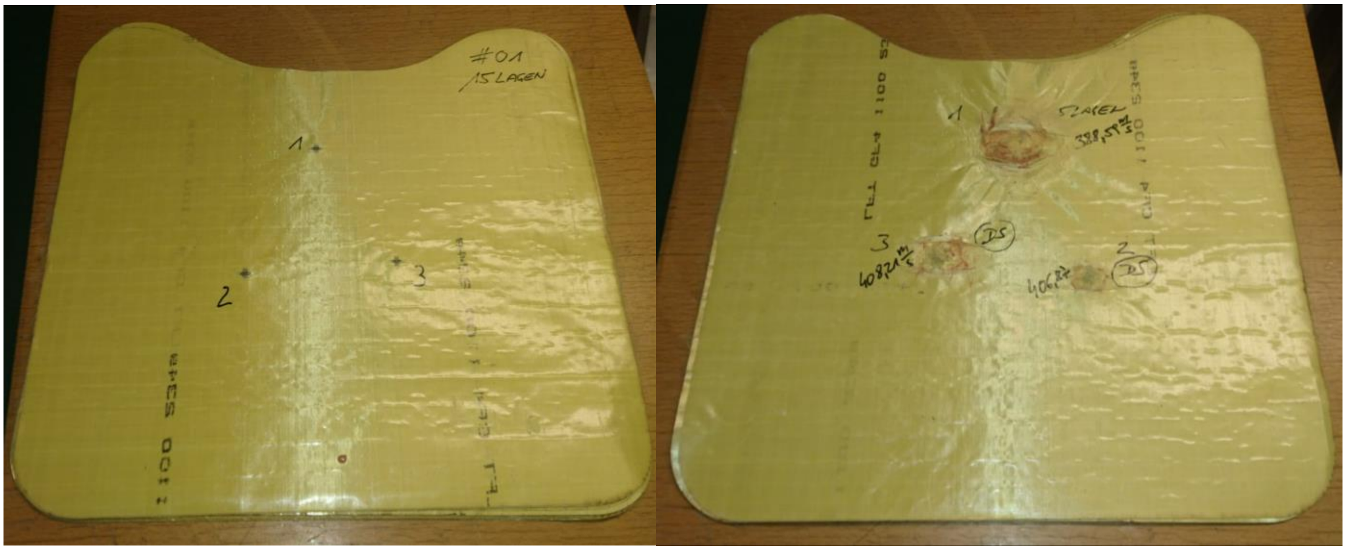

Figure 10. Left side: the frontside of test number 13. Right side: the backside after the shooting. Readable on the backside is the stuck layer (DS means perforation) and projectile velocity.

Figure 11. Deformed projectile of test number 12M.

VIII. DISCUSSION

The pre-testing and pre-ballistic test resulted in following findings. 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 IV). 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 V).

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 meets this requirement by far (Table VI). 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 plats. In further ballistic tests they have to be verified for the VPAM 4 level.

The ballistic test with the new materials confirms that the 15-layer Dyneema® HB solution meets the VPAM 3 and BSW regulations. In fact, the average amount of transmitted energy is 29.6 J. This is only 40 % of the allowed value and 12 % less transmitted energy compared to the HB26 plates. Thus, HB50 shows a promising ballistic performance to meet VPAM 4 regulations, which have to be tested in future work. Moreover, because of the lower density, the shirt patterns out of HB50 are 11.4 % lighter, compared to the predecessor material.

The SB115 solution showed good first-shoot-capabilities, with the lowest transmitted energy of the ballistic test but a perforation after the second and third shoot. Thus, SB115 missed the requirements of VPAM BSW and will no longer be considerate in the project.

IX. 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. The conducted pre-tests (heat and sag test) show that the 15-layer plate meet our expectations the best, in the area of flexibility and durability. This leaded to further ballistic tests with 15-layer thick plates. Especially, the ballistic results of the plate are promising. The patterns out of this material already meet the requirements of VPAM 3 and VPAM BSW. Furthermore, compared to other available products on the market, the new plate has a reduced weight of ~150 g, is 1.2 mm slimmer and full flexible.

Further scientific work, will be focused on the HB50. This includes that 15-layer sweatshirt patterns made of HB50 will be extensive ballistic tested. Especially, VPAM 4 and VPAM BSW testing will be focused. A flatter and wider back-face-deformation imprint is strived. Moreover, the heat and sag test for this material will be done, in order to get sure about the material properties relating durability and flexibility. For all these tests, 15-layer sweatshirt patterns will be produced with the lamination process by hand. Afterwards, the finalization process will be begun. This process includes investigations of coatings and edge support, to protect the ballistic plates against environmental conditions and make them ready for mission.

REFERENCES

[1] H. Seeber and A. Ramezani "Development of Flexible and Lightweight Ballistic Body Armor, Constructional Contributions for Ballistic Components out of Ultra-High-Molecular-Weight Polyethylene", The Tenth International Conference on Advances in System Simulation (SIMUL2018) IARIA, pp. 46-52, Oct. 2018.

[2] Gun Violence Archive, "Past Summary Ledgers", [Online]. Available from: http://www.gunviolencearchive.org/past-tolls [09.2018].

[3] L.H. Nguyen, "The Ballistic Performance of Thick Ultra High Molecular Weight Polyethylene Composite". RMIT University, Dec. 2015.

[4] H.v.d. Werff and U. Heisserer, "High performance ballistic fibers: Ultra-High Molecular Weight Polyethylene (UHMWPE)" in "Advanced Fibrous Composite Materials for Ballistic Protection", First Edition. Woodhead, Oct. 2016.

[5] DSM Dyneema, "Product Specification Sheet HB26", Feb. 2014.

[6] DSM Dyneema, "Product Specification Sheet HB50", Feb. 2014.

[7] DSM Dyneema, "Product Specification Sheet SB115", Feb. 2014.

[8] T. Tam and A. Bhatnagar, "High-performance ballistic fibers and tapes" in "Lightweight Ballistic Composites: Military and Law-Enforcement", Second Edition. Amsterdam: Elsevier, May. 2016.

[9] M. Hendrix and M. Herzog, "Ballistic Behavior of Soft-Ballistic UHMWPE" ("Schutzverhalten von weich-ballistischen ultrahochmolekularem Polyethylen"), in "Wissenschaftliche Beiträge 2018", Technical University Wildau, Mar. 2018.

[10] HP-Textiles, "HP-R15GB-flex Data Sheet", Aug. 2017.

[11] EOSDIS Worldview, "Land Surface Temperature (Day)" [Online]. Available from: https://go.nasa.gov/2P3DxzW [09.2018].

[12] Association of test laboratories for bullet resistant materials and constructions (VPAM), "VPAM APR 2006 Version 2", Nov. 2014.

[13] Association of test laboratories for bullet resistant materials and constructions (VPAM), "VPAM BSW 2006", May. 2009.

[14] Association of test laboratories for bullet resistant materials and constructions (VPAM), "VPAM PM 2007 Version 2", Jan. 2014.