

Ballistic, mechanical and BABT related properties of UHMWPE helmet shells based on novel matrix systems

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Abstract

It is generally known that Ultra High Molecular Weight Polyethylene (UHMWPE) materials exhibit better ballistic stopping power than aramid counterparts on a weight basis. Besides the higher ballistic properties in protective helmets, however, most UHMWPE materials in earlier studies were reported to demonstrate higher back face deformations and lower rigidity of the ballistic shell, e.g. in a side-to-side compression test. This raised concerns about Behind Armour Blunt Trauma (BABT) for UHMWPE helmets.

With the continued development in the field of UHMWPE laminates, new matrix systems and processing technologies have resulted in strongly improved mechanical properties. A contribution at the PASS 2023 showed that with the right design and processing an UHMWPE helmet shell at attractive areal density can stop 7.62x39mm AK47 Mild Steel Core projectiles at muzzle velocity.

This year's paper provides a performance comparison between helmet shells from European NATO fielded aramid helmet systems on the one hand, and Avient in-house UHMWPE helmet shells manufactured with deep draw technology on the other. The UHMWPE unidirectional material uses a novel matrix system for enhanced mechanical performance. Both helmet systems make use of identical suspension systems. Ballistic testing is executed against 1.1 g Fragment Simulating Projectiles (FSP). Considering BABT, side-to-side compression tests and the effect of 9 mm FMJ DM41 projectile impact on dynamic back face deflection, back face signature (in a witness medium) and transmitted impact forces to a Biokinetics Ballistic Load Sensing Headform are evaluated.

Ballistic testing shows that the UHMWPE helmet shells exhibit at least 20% higher V_{50} against 1.1 g FSP, while being 20% lighter than the tested aramid helmet shells. In addition, the results show that the lighter helmet shell made with UHMWPE material and the novel matrix system for enhanced mechanical performance is on par with the fielded aramid helmet shell on all the above mentioned BABT criteria.

1. INTRODUCTION

Since ages, combat helmets are a crucial part of personal protection equipment. The requirements have changed over time in line with methods of warfare and threats and evolved with development of manufacturing methods and materials. What started as a means of protection to sword strokes, arrows and musketry assault threats changed during World War 1. Combat helmets evolved to protect against shrapnel, debris and small calibre ammunition, as it proved that many fatal head wounds were not caused by impact of bullets or direct blows but by small, limited energy containing fragments. Most recently, protection against rifle threats has been added to the possibilities that modern materials like Ultra High Molecular Weight Polyethylene (UHMWPE) and state of art production processes can provide.

The helmet of today has developed to a system that provides several functions:

- mounting for accessories like communication devices and night-vision goggles
- protection to regular blunt impact
- stopping various threats such as fragments, small calibre and rifle threats.
- Behind Armour Blunt Trauma (BABT) protection

The main function of combat helmets today is to provide protection against fragments. It is generally known that UHMWPE materials exhibit better ballistic stopping power than their aramid counterparts [1,2] on a weight basis. Next to the pure stopping power, also the resistance against deformation is important. In the past, UHMWPE materials were reported to demonstrate higher back face deformations and lower rigidity of the ballistic shell, e.g. in a side-to-side compression test compared to alternative materials. These observations gave rise to concerns and speculations about BABT for helmets made from UHMWPE.

This paper aims to evaluate and compare helmet shells from European NATO fielded aramid helmet systems on the one hand, and Avient in-house moulded UHMWPE helmet shells on the other. The UHMWPE helmet shells are manufactured with a unidirectional (UD) material, based on a novel matrix system for enhanced mechanical performance.

The same test and evaluation methods are applied to both the UHMWPE and the aramid helmet shells for comparison purposes.

2. HELMET SELECTION

For the various tests, two series of helmet shells are selected:

- The Series #1-aramid is a military combat helmet shell made from plain weave aramid prepregs with a mass of 455 g/m², single side coated with 12% toughened phenolic resin. The fibre used is 3140 dtex Kevlar[®] 129. The shells are moulded into an Advanced Combat Helmet (ACH) shape using a flower cut process. Moulding conditions are in line with guidelines provided by the raw material supplier.
- The Series #2-PE is a helmet shell made from Dyneema[®] HB30 unidirectional composite (APM). The composite consists of first generation 1760 dtex UHMWPE yarns, embedded in a novel thermoplastic matrix system. The mass of the UD composite material is 266 g/m². The proprietary matrix system can be categorized as a polyolefin matrix system with tailored mechanical and ballistic properties, providing a stiffer composite than legacy first generation PE UD composites. The helmet shells are manufactured in an R&D facility in the Netherlands, making use of the available deep draw helmet manufacturing process [3].

These two series of helmets are selected to make an objective comparison between two materials, targeting similar protection levels with similar designs. Admittedly, aramid helmets of this performance level (mass, areal density, V50, mechanical properties) are around for more than 10 years, but still represent the state of the art in ballistic protection and mechanical performance for aramid helmets. This helmet type is still being manufactured commercially and supplied to NATO end-users today. Likewise, the PE fibres are of the first generation, while to date Dyneema[®] composite materials are available with second and third generation fibres, with increased strength and protection level. The HB30 composite is designed for applications like a standard military combat or police helmet (fragment, handgun protection), whereas later generations target higher threat levels, such rifle threats [3], or lower weight shells. Helmets made with HB30 are also being manufactured and supplied to NATO end-users today.

Table 1 shows some characteristics of the helmet series selected for this study. The helmet shells of both series exhibit an overall thickness of approximately 8 mm. At roughly similar thickness, the Series #2-PE helmet shell is 23% lighter compared to the helmet shell of Series #1-aramid.

Table 1: Key parameters of the helmet shells used in the study

Type	Base material	Shell thickness [mm]	Total area [cm ²]	Helmet shell mass ⁱ [g]	Shell AD ⁱⁱ [kg/m ²]
Series #1-aramid	Aramid, woven Kevlar [®] 129	7.5	1182 (100%)	1130 (100%)	9.6 (100%)
Series #2-PE	UHMWPE composite HB30	7.8	1216 (103%)	872 (77%)	7.2 (75%)

Both helmet shells resemble a size L helmet. The geometry of the helmet shells of both series is not fully identical though; small differences in the shape do exist. Figure 1 shows both helmet shells.

Both helmet systems were tested with identical suspension systems. Where applicable for the tests, the helmet shells of both series are equipped with a pad system: Team Wendy[®] ZORBIUM[®] Action Pad (ZAP[™]) 7-Pad NSN Liner System (3/4inch) [8]. The typical pad configuration is shown in Figure 2. A helmet strap system is used to fixate the helmet shells for ballistic testing where applicable.

ⁱ Shell mass excluding padding and suspension system

ⁱⁱ Areal Density

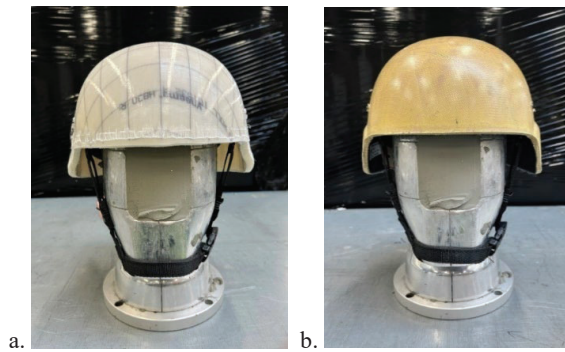


Figure 1: Helmet shell including strap and padding system mounted on NIJ head form (a. UHMWPE helmet shell. b. Aramid helmet shell)

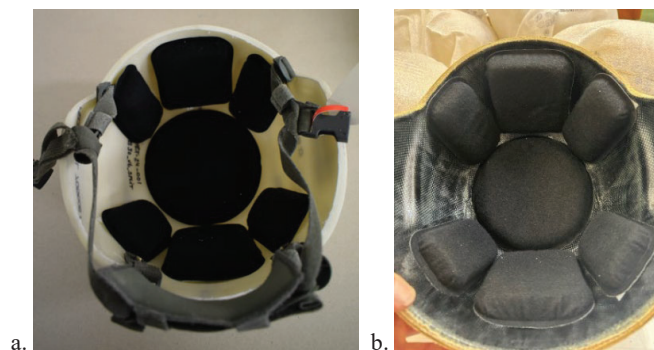


Figure 2: Typical padding configuration (a. UHMWPE helmet shell. b. Aramid helmet shell)

3. TEST METHODS

To evaluate helmet shells of both series, ballistic testing is executed against 1.1 g Fragment Simulating Projectiles (FSP). Considering BABT [4,5], testing is performed with 9 mm Full Metal Jacket (FMJ) DM41 (Ruag Ammotec) projectiles. In summary, five different test methods are used to evaluate the helmet shells:

- a. Fragment V_{50} performance executed against 1.1 g FSP.
- b. Back Face Signature (BFS) measurement in a witness medium (against clay) with 9 mm FMJ DM41 projectiles
- c. Side-to-side compression [7]
- d. Dynamic Back Face Deformation (BFD) measurements with Digital Image Correlation (DIC) with 9 mm FMJ DM41 projectiles
- e. Measurements of the transmitted impact forces to a Biokinetics Ballistic Load Sensing Headform (BLSH) [6] with 9 mm FMJ DM41 projectiles

The fragment V_{50} performance measurement (a) and BFS measurement (b) are executed at Avient's ballistic shooting range in The Netherlands. All other tests (c, d and e) are carried out at TNO Laboratory for Ballistics Research in The Hague, The Netherlands.

Table 2 presents the number of helmets tested in each test and the amount and type of fired projectiles. In total 24 helmet shells are tested and 116 projectiles are fired.

Table 2: Overview of the number of helmets tested and projectiles fired per test

Test	Helmets		Projectile	
	Series #1- aramid	Series #2- PE	1.1 g FSP	9 mm FMJ DM41
Fragment V_{50} performance	4	4	72	-
BFS in a witness medium	2	2	-	16
Side-to-side compression	2	2	-	-
Dynamic BFD with DIC	2	2	-	16
Transmitted impact forces to a BLSH	2	2	-	12

3.1 Fragment V_{50} performance

To study the 1.1 g FSP V_{50} performance a method derived from STANAG 2920 test procedure [9,10] was used.

The helmet shell without suspension system is mounted in a three-point fixation platform and fixated by clamping it at three points.

The projectile used for the test is a 1.1 g FSP. Each helmet shell is tested according to a standard shot pattern (according to Avient's internal test protocol) on nine locations per helmet. Table 3 presents the typical shot sequence and the distance to the edge at the shot location. The shot-to-shot distance is 8-10 cm. Four helmet shells are tested for both series. The test is executed without backing material; precautions are taken to prevent any complete penetration from damaging the opposite side.

Table 3: Overview of shot sequence and distance to edge

Shot #	1	2	3	4	5	6	7	8	9
Location	Front	Left	Back	Right	Front/ left	Back/ left	Back/ right	Front/ right	Crown
Height to edge [cm]	6	8	6	8	11	13	13	11	-

In this specific study the STANAG 2920 is the method used for the determination of the V_{50} . The definition of V_{50} is the velocity at which the probability of perforation of the chosen projectile is 50%. The V_{50} is calculated by using a probit analysis over all measurements on all shot locations.

3.2 BFS in a witness medium

For the BFS in a witness medium the following method is applied (derived from the "Bullet Resistance Helmet test procedure" - HPW-TP-0401.01B [11]).

For this test, a head form (referred to as the National Institute for Justice (NIJ) head form) is used. The metallic head form is configured for the deformation test and has sagittal and coronal slots or cavities in the head form. Prior to the test, the slots or cavities of the head form are filled with Roma Plastilina nr.1 (calibrated) as described in the NIJ-STD-0101.06 standard [12] and shaped to the contour of the metallic head form. The impact test headform is specified as a size 7 ¼ for testing. The corresponding head circumference of 57.9 cm corresponds to the size L helmets used.

The complete helmet, including strap and pad system, is attached to the head form as it would be attached to the head of the user in a normal operational scenario. After each shot, the indentation or deformation of the clay is measured and recorded.

The projectile used for the test is a 9 mm FMJ DM41 at a speed of 430 ± 9 m/s. Each helmet is tested according to the same shot order before another helmet was tested; the test order is front, left, back, right. The shot locations are indicated on the helmets and have a similar distance to the edge of the helmet shell for both series (front: 6.0 cm, left/ right: 9.5 cm, back: 6.5 cm). Orientation of the impact is perpendicular to the helmet shell surface at the shot location.

3.3 Side-to-side compression

The test method used to measure the rigidity of the helmet is a compression test [7] performed on a Constant Rate of Extension machine. An example of the test setup is shown in Figure 3.



Figure 3: Side-to-side compression test setup with UHMWPE helmet shell sample.

The helmet shell under test is placed in the equipment used for the compression test. Placement is such that compression is executed at the widest point of the helmet. The helmet shell is supported by a plate on the crown. The compression test starts by compressing at a prescribed rate from side-to-side (ear-to-ear) until a pre-defined force is reached (1334 N or 300 lbf). As soon as the pre-defined force is reached, the equipment reduces the force to 22 N (or 5 lbf). This compression cycle is repeated 24 times. The load levels and number of cycles are chosen as such for reasons of comparison to earlier measurements.

Within five minutes after the completion of these 24 repetitions, the distance from the left-hand side to the right-hand side (ear-to-ear) of the helmet is measured (measurement C) and compared to the reference distance measured prior to the test sequence (measurement A). Subsequently, no force is applied on the helmet under test for 24 hours. After this period, the distance from the left-hand side to the right-hand side of the helmet is measured again (measurement D), compared to the reference and reported. A value $C-A$ can now be considered as the remaining deformation directly after the test. The value $D-A$ can be considered as the remaining deformation after 24 hrs.

3.4 Dynamic BFD with DIC

To demonstrate how the deformation develops during the impact of a bullet, a dynamic BFD measurement including DIC is performed. The deformations during the dynamic BFD test will, in contrary to the measurement of the BFS in a witness medium as described in section 3.2, not be affected by any contact between the deforming helmet surface and the witness medium itself

To study the dynamic BFD with DIC, two helmet shells of each series are prepared for the test to perform a duplicate measurement. The helmet shells do not contain a suspension system. The areas surrounding the shot locations are covered with a random speckle pattern at the inside of the helmet (see Figure 4a). The pattern is manually applied by using a permanent marker; this provides a pattern that adheres well enough to the helmet inner surface and the colour of the pattern is chosen to provide sufficient contrast with the inside surface of the helmet shells.

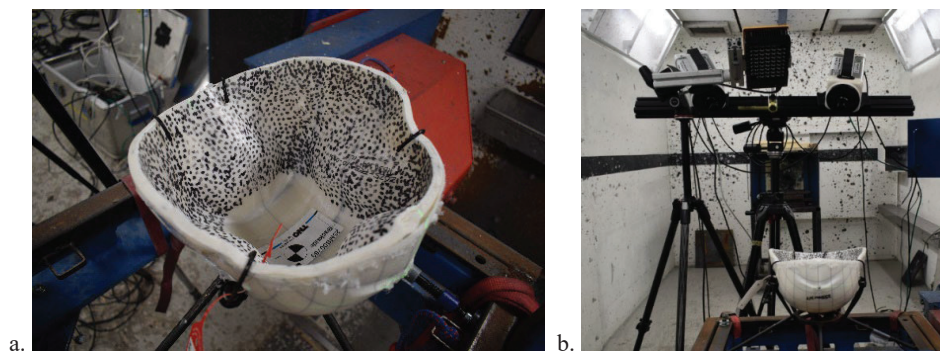


Figure 4: Dynamic BFD test
(a. Speckle pattern on UHMWPE helmet. b. Typical dynamic BFD test set-up)

The prepared helmet shells are placed on a fixture with the crown facing downwards. Two cameras are oriented towards the inside of the helmet shell and trace the bulging of the helmet shell during impact. In Figure 4b the dynamic BFD setup can be seen. The frame rate of the cameras recording the event is 30,000 frames per second (fps). DIC software is used to extract the data from the test.

The projectile used for the test is a 9 mm FMJ DM41 at a speed of approximately 430 m/s. Each helmet is tested according to the same shot order before another helmet was tested; the sequence is front, left, back, right. The shot locations are indicated on the helmets and have a similar distance to the edge of the helmet shells for both series (front: 6.5 cm, left/ right: 11.0 cm, back: 7.0 cm). Orientation of the impact is perpendicular to the helmet shell surface at the shot location.

3.5 Transmitted impact forces to a BLSH

Next to BFS/ BFD, also the force exerted on the head during projectile impact is an important criterium for manufacturers and end users, as it is linked to Behind Armour Blunt Trauma. This paper does not investigate the link between BFS/BFD and BABT, nor aims at estimating which severity of the force is acceptable. However, this paper does compare any differences in the transmitted forces to the head during back face deflection by using the BLSH [6].

To perform a duplicate measurement, two helmets of each series are prepared for the test. All helmet shells are equipped with a full suspension system. Each helmet is shot on three locations: front, back and right side. For the latter location, a second BLSH with sensors mounted for side impact measurement is used. The shot locations are determined based on the position of the central sensor on the BLSH.

Close attention is paid to:

- using the same pad system and it's positioning.
- similar positioning of the helmet shell on the BLSH.

The projectile used for the test is a 9 mm FMJ DM41 at a speed of approximately 430 m/s. Each helmet is tested on the front side first. After execution of all front tests, all helmet shells are tested on the back side and subsequently on the right side of the helmet shell. Orientation of the impact is perpendicular to the helmet shell surface at the shot location. Per test, the individual sensor readings are added to give the total force.

4 TEST RESULTS

In this section, the results of the individual investigations are presented and discussed. No pass or fail criteria are applied on the results, as the tests serve for quantitative comparison only.

4.1 Results on Fragment V₅₀ performance and BFS in a witness medium

The fragment V₅₀ performance measurement and the BFS measurement in a witness medium are tested according to the methods described above. In Table 4 the V₅₀ is reported for both series as well as the average indentation on the different shot locations. All underlying test reports used for this study [13-15] are available from the authors upon reasonable request.

Table 4: Overview of test results

Type	Helmet shell mass [g]	1.1g FSP V ₅₀ Avg. [m/s]	Average BFS [mm] (Min. value/ Max. value)				
			Front (6.0 cm from edge)	Left (9.5 cm from edge)	Back (6.5 cm from edge)	Right (9.5 cm from edge)	Avg.
Series #1-aramid	1130 (100%)	682 (100%)	20 (20/21)	9 (7/11)	14 (12/15)	10 (8/13)	13.2
Series #2-PE	872 (77%)	841 (123%)	18 (17/19)	10 (9/11)	15 (12/17)	12 (8/15)	13.8

The results in Table 4 show that for the UHMWPE helmet shells, with 23% lower mass, the ballistic stopping power is at least 20% higher compared to the aramid counter parts. These results confirm the better ballistic stopping power of UHMWPE materials.

From the results in Table 4 it also is apparent that the deformation for the sides is smaller than for the front and the back, with the maximum deformation for the front impact. There are multiple potential explanations for that:

- The sides of the helmet experience an additional stiffening from the shape of the ear section leading to lower deformations.
- The curvature is different for the various impact locations. The curvature is highest on the front and back side. The material on the front and back experiences more free length before the material is tensioned during the bulge formation.
- The front and back section are shot more closely to the edge, when compared to the locations on the sides. This would typically mean that less material is available to carry the load.
- The front location is located more towards the crown compared to the back side and as such can experience a negative influence from the additional curvature towards the crown.

Which of these effects is the most dominant with respect to the observed deformation behaviour is not investigated in detail.

The results in Table 4 also demonstrate that the BFS of both Dyneema® HB30 based UHMWPE helmet shells show similar deformation values as the aramid helmet shells, despite the lower mass of the UHMWPE shell.

4.2 Results on side-to-side compression

In Table 5 the average results of the side-to-side compression measurement are reported for both series.

Table 5: Overview of side-to-side compression results, average values per series

Type	Remaining deformation after load cycle completion (C – A) [mm]	Remaining deformation after a 24-hour recovery period (D – A) [mm]
Series #1-aramid	1.0	1.0
Series #2-PE	0.0	0.0

The results in Table 5 show that the UHMWPE helmet shells based on the novel matrix system perform similar compared to their aramid counterparts in the side-to-side compression test. Helmet shells of both series exhibit almost absent remaining deformation levels.

4.3 Results on Dynamic BFD with DIC

A typical result of the DIC measurement is shown in Figure 5.

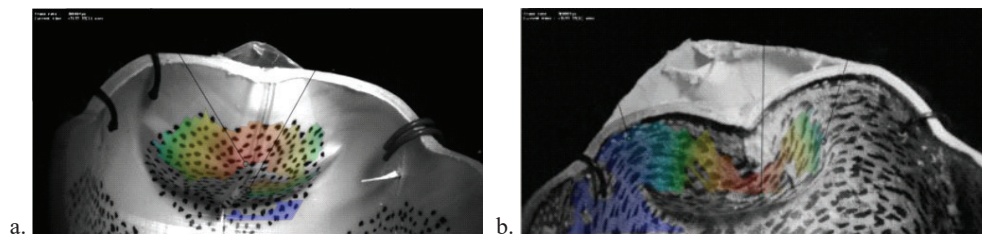


Figure 5: Typical deformation pattern result of the DIC measurement in front impact (a. UHMWPE helmet shell. b. Aramid helmet shell)

The peak deformation values from the DIC analysis as obtained from the recorded videos are shown in Figure 6 below. Values are normalized with respect to the maximum occurring value of all tests (i.e. the

displacement of helmet 1 of Series #1-aramid in a frontal impact). In case no value is plotted, no measurement is available from the DIC analysis.

The deformations occurring during the dynamic BFD measurement are larger than the deformations during the BFS measurement in a witness medium. An explanation for this is that the helmet shells can deform without any counter pressure from the witness medium during the dynamic BFD measurement.

For the dynamic BFD a similar trend can be seen as for the results presented for the BFS measurement in a witness medium in section 4.1. For the dynamic BFD measurements, the deformation for the sides is smaller than for the front and the back, with the maximum deformation for the front impact. Similar potential explanations for this difference in deformation can be given as in section 4.1.

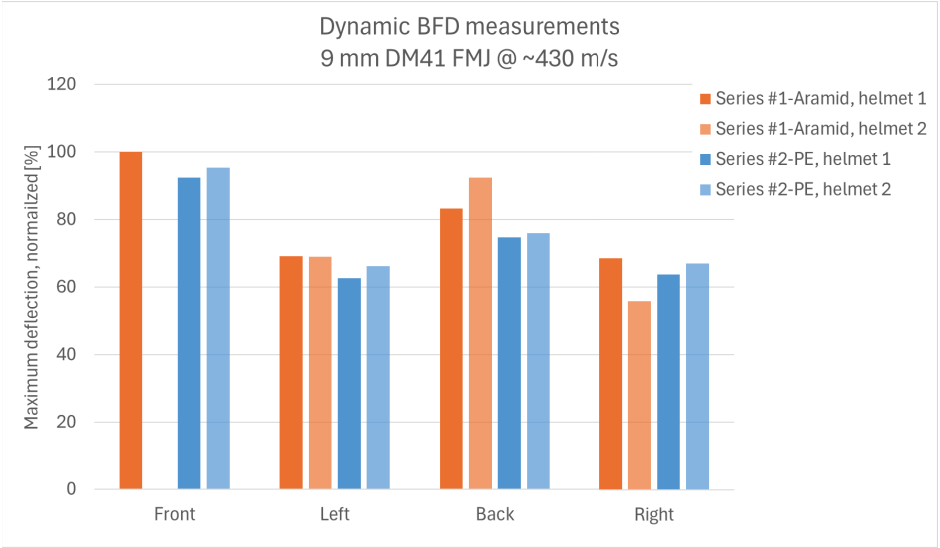


Figure 6: Overview of peak deformations for the dynamic BFD tests at 430 m/s projectile velocity

The relative comparison of the dynamic BFD measurement for both series shows that the deformations for the UHMWPE helmet shells are similar or less compared to their aramid counterparts for all four test locations.

4.4 Results on Transmitted impact forces to a BLSH

The transmitted impact forces to a BLSH are tested as described above. A typical result of the BLSH measurement is shown in Figure 7.

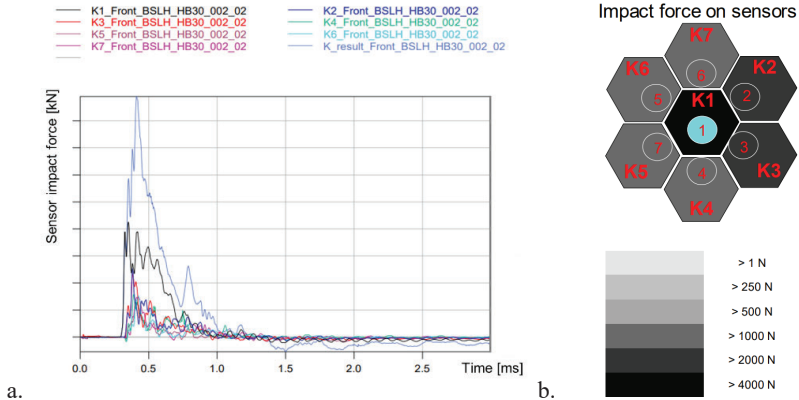


Figure 7: Typical result of a BLSH measurement (front impact on UHMWPE helmet shell) (a. sensor impact force data. b. sensor pad orientation)

From the unfiltered measurements, the maximum occurring (peak) total force is derived and plotted for each test in Figure 8. Values are normalized with respect to the maximum occurring value in all measurements (i.e. the maximum occurring force of helmet 1 of Series #1-aramid in a frontal impact). Measurements for the left side are not available as deformation of the helmet on the other locations prevents correct positioning of the helmet on the BLSH.

Figure 8 shows that the forces transmitted from the helmet shell to the sensors on the head form are similar, except for the front side where the force exerted by the UHMWPE helmet shell is less compared to the aramid counterparts.

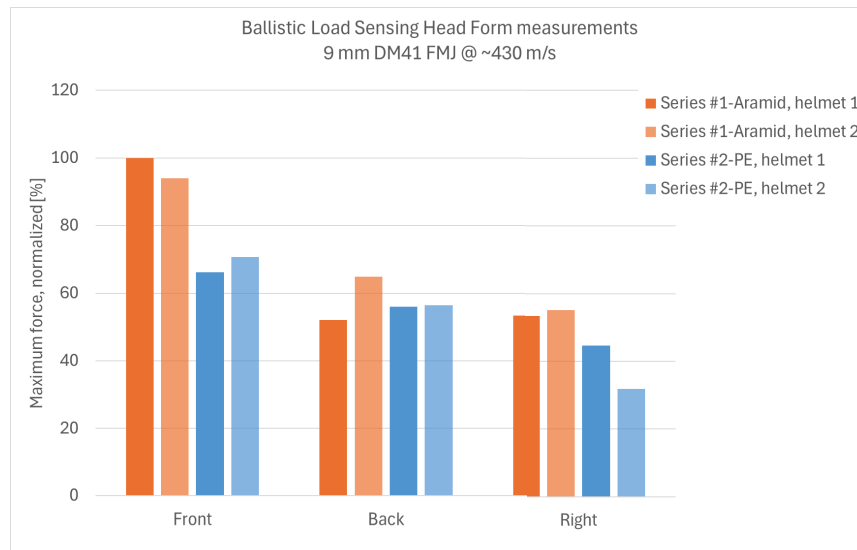


Figure 8: Overview of maximum force for the BLSH tests at 430 m/s projectile velocity.

Differences in performance on the BLSH can not be fully attributed to the material performance per definition. Variation in size can have an influence on the transmitted force. The distance between the BLSH and the helmet inside surface at the actual shot location is not recorded prior to the test. As the aramid helmet shells are slightly wider, the aramid helmet series may exhibit a larger distance between shell and sensor and can benefit from this to generate lower impact forces on the side. Front-to-back, the UHMWPE helmets are slightly larger which can have an influence on the measured forces. As the differences in size are small compared to the deformations reported in section 4.3, the effect of variations in size on the transmitted forces is expected to be small.

On the front and back side, the helmet pads are located beneath the impact location, which is not the case for the side location. Whether variations in transmitted force on the front side can be attributed to different contact area between the pads and the sensor due to a different local curvature is not investigated in this study.

5. CONCLUSIONS

Based on this study, it can be concluded that the ballistic resistance of helmets using UHMWPE based material for fragments can be more than 20% higher, while being more than 20% lighter than the tested aramid helmet shells. At this weight benefit, UHMWPE helmet shells making use of novel matrix systems exhibit at least similar BFS compared to their aramid counterparts. This is confirmed with test results from measurements of the BFS in a witness medium as well as from measurements of the dynamic BFD measured with DIC. The results from the side-to-side compression test complete the picture that UHMWPE helmet shells based on novel matrix systems perform similar compared to their aramid counterparts and exhibit very low remaining deformation levels after the test. From this investigation, it is also concluded that the UHMWPE helmet shells overall demonstrate similar or slightly lower forces on the head sensors in the instrumented head form.

In summary, compared to their aramid counterparts, at similar thickness, but at 23% lower mass, the helmet shells made from Dyneema® HB30 demonstrate higher resistance to penetration while providing similar BFS/ BFD, similar transmitted force levels and similar permanent deformation after side-to-side compression.

Because of the presented results, procurers, manufacturers and end users are provided with additional possibilities compared to their existing aramid solutions:

- a lighter UHMWPE helmet with increased resistance to penetration at similar BFS and transmitted force levels.
- a UHMWPE helmet at similar mass, but with an increase of the resistance to penetration at increased stiffness levels, lower BFS and lower transmitted force levels.

For future research it is important to note that with reaching increased protection levels at lower mass and lower helmet thickness, the levels of BFS and corresponding transmitted force levels are of increased importance. With the onset of the wish and the possibility to stop higher threat levels, additional investigations and research are needed to understand and define acceptable levels for the BFS and transmitted force levels to prevent BABT. For future helmet systems, manufacturers would benefit from a clear definition of projectile calibres, projectile speeds and test methods that should be used to evaluate helmet performance in terms of BFS, transmitted forces and the corresponding BABT.

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