Advances in the Development of Combat Helmet Systems

Constructional Contributions for Lightweight Ballistic Composites

Short Paper

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***Abstract*—In the military and police sector, the endangerment for the forces has risen over the last decades. Especially police forces are facing new threats due to increased terrorist activity in western European cities and a rising propensity to violence. This development makes it necessary to provide state of the art protection for patrol officers. This includes helmets made of ultra-high molecular weight polyethylene (UHMWPE) to lower the overall weight of equipment and increase the combat value of the forces by providing more comfort and possibilities for attachments. At the moment, these types of helmets are not ready to fulfill the required level of protection against projectiles. The intention of this paper is to give background information about these new threats and to mention first ideas how to tackle the emerging problems of current UHMWPE combat helmets. In addition, early results regarding the process of UHMWPE will be presented.**

Keywords - applied research; fiber-reinforced plastics; optimization; armor systems; ballistic trials; material processing; post-processing.

I. Introduction

Combat helmets are a key factor in personal protection for military and police forces. Rapidly changed threats on missions, especially for police patrol officers and soldiers in stabilization missions, prove that protection needs a new ability profile [1]. This work provides background information to specify the problems and first ideas how to solve these. Later on, findings and required settings for pre- and post-processing UHMWPE will be shown. The overall aim is to create a ballistic combat helmet that meets VPAM 3 regulations (the third level of ballistic protection of the European "union of test centers for armored materials and constructions") and the technical directive “System Ballistic Helmet” 5/2010 [2].

II. Structure of the Paper

Section III gives a brief information about the history of combat helmets and their materials through time. In Section IV, threats for ballistic protection are mentioned. Section V is about the disadvantages of current UHMWPE combat helmets and Section V deals with the advantages of lighter polymer combat helmets. In Section VII, the aim is concretized and explained. In the final section, Section VIII, the steps in the development process of a combat helmet are described. In addition, findings in the processing and post-processing of UHMWPE are pointed out.

III. History

Combat helmets have a long tradition. Before the invention of gunpowder, they were used as a protection against blunt trauma and cuts. They were designed to deflect, e.g., a sword, so there was less residual energy on the head. Later on, helmets were mainly worn for pageantry and unit recognition until the First World War began.

A. Combat Helmets in the 20th Century

Due to the massive use and increased lethality of artillery, the German forces introduced the “Steel Helmet Modell 1916” in 1915. All nations introduced nearly the same helmet models in at this time, which were made of basic steel. These helmets were only able to stop the primary threat of that time: fragmenting projectiles of artillery bombs. They were not able to stop bullets because of the available materials. During the Second World War, the U.S. Military introduced the M1 in 1943, which was made out of “Hadfield steel” (see Figure1). This helmet was used by the German armed forces until the 1990s. On the one hand, problems with this type of steel helmet occurred because the helmets were too heavy and reduced the view, hearing and mobility of the solider. On the other hand, the helmet provided reliable protection against light and medium fragments. The M1 was followed by a very new generation of combat helmets, which was made of aramid. Aramid was the first synthetic bulletproof material and was invented in the 1960s by DuPont [3].

B. Combat Helmets in the 21st Century

As a replacement of the M1, the US-Military introduced the “Personnel Armor System for Ground Troops” (PASGT), was made of aramid. In addition, they used the new retention system “NOSHA”, which provided a better shock absorption and air circulation. The German armed forces introduced this type of helmet system as well, called “Combat Helmet, Ground Forces”. This helmet system is barely able to stop fragments and 9mm bullets, but the residual energy is still too high and as such, the helmet cannot provide reliable protection against aforementioned threats. The “Advanced Combat Helmet” (ACH) primary has a new suspension system to improve protection against blunt impacts. Additionally, the design changed to allow the usage of new equipment, such as ear protection and radio systems. The next stage of development was – again – a totally new material: the ultra-high molecular weight polyethylene fibers (UHMWPE). This material combines low weight (areal density: ~86.18 N/m^2) with high strength (tenacity: ~34g/d) [4]. With hybridization techniques, the U.S. Military developed a new generation of combat helmets in 2010, the so-called “Future Assault Shell Technology” (FAST). The German armed forces also use FAST with the name “Combat Helmet Special Forces”. Also, FAST helmets were added to the concept “Infantry of the Future” (see Figure 2) [5]. FAST helmets have been designed and developed with special forces and air borne units in mind. The helmet system only provides protection against light fragments and blunt impacts. The retention system has been upgraded to a multi-pad four-point retention system. This leads to reduced weight and higher comfort for the soldier. In 2012 the “Enhanced Combat Helmet” (ECH) was developed. Due to the hybridization of fiber composites, the helmet is able to withstand ballistic threats. However, the residual energy of a projectile is still too high, which leads to back-face deformation and life-threatening injuries. The Heads-Up helmet system introduced in 2013 aims to protect the entire head and paves the way for a new trend. The current generation of helmets mainly protects the wearer against fragmentation. Combat helmets are developed in order to increase combat effectiveness of the individual soldier. In the future, this should extend to protection from blast and ballistic threats while having fully integrated attachments such as communication systems, ear protection or a head-up display [3].

	M1 Steel Pot 1943	PASGT 1980	ACH 2005	FAST 2010	ECH 2012	HEADS UP 2013	FUTURE 2018
Helmet Design							
Helmet Materials	Hadfield Steel	Aramid Fiber (Kevlar®)	Improved Kevlar®	UHMWPE (Dyneema®) and Carbon Fiber		Future S&T efforts focused on more comprehensive head protection (ballistic/blast/blunt trauma)	
Helmet Threats	Fragmentary rounds and .45 M1911 bullet	Fragmentary rounds, 9mm		Fragmentary rounds	Fragmentary rounds, 9mm and specified small arms	Fragmentary rounds at lighter weight, small arms	Address blast as well as ballistic threats
Areal Density	2.2 psf	2.2 psf	2.2 psf	1.8 psf	2.2 psf	1.6 - 1.8 psf	TBD
Tenacity	----------	23 g/d	27 g/d	34 g/d	37 g/d	37 g/d	TBD
Significance	Used in WWII, Korea, and Vietnam	Material revolution: synthetic ballistic material	Changes in design and suspension, improved aramids	Distinctive innovations in design and materials	First helmet with specified frag and small arms protection	Attempting extensive/ integrated head protection	Overarching improve-ments in head protection

Figure 1. Evolution of modern combat helmets

Figure 2. FAST helmet with the concept "Infantry of the Future" [5].

IV. New Threats

A. Changed Threats for Police Forces

Threats for police forces and military troops have changed a lot over the last decades. Police forces face international terrorism, especially in western European cities. More and more, terrorists are professionally trained and equipped with military weapons and gear. Time is the most crucial point in hazardous situations, so patrol officers have to engage first [5]. Only a combination of ballistic vests and ballistic helmets provides the necessary level of protection in such situations. Especially patrol officers are facing unpredictable threats on duty, so their helmets have to provide protection against multiple threats. Apart from this, hits with blunt and sharp weapons, fire and chemicals are common risks for them. The willingness of patrol officers in Baden Wurttemberg to wear their helmets also in common situations like brawls and skirmishes makes it necessary to provide good shock absorbing attributes against blunt trauma [1][6].

B. New Threats for Military Forces

Military forces are facing changed threats. Statistics of the American operations in Afghanistan and Iraq show that head and neck wounds are increasing. The distribution shows that 30% of all wounds are in the head and neck area (based on injuries/treatments from hospitalization, including persons who died of wounds) [3]. The main threats at patrol missions are improvised explosive devices (IED) and ambushes with assault rifles. Due to the increased use of IEDs, blast associated head injuries, e.g., fragments have increased compared to gunshot wounds. Furthermore, the characteristics of the fragments have changed compared to mortar and artillery shells. This can lead to a different impact behavior. In addition, blunt traumatic injuries have increased because they are linked to blast events. Nevertheless, blunt trauma is also associated with non-combat situations like vehicle crashes, parachute drop accidents or falls. Common blunt trauma threats have an impact velocity of 6.1 m/s, which is equal to a drop of 1.9 m [3]. The primary ballistic threat is caused by assault rifles of type AK-47 (7.62x39-mm) and owing to the increased close combat situation pistols emerging as threats, for example, Makarov (9x18-mm) or Tokarev (7.62x25-mm). Altogether, the America Department of Defense locates the main threat of infantry weapons at 5.56-mm and 7.62-mm rounds and muzzle velocity from 735 m/s to more than 800 m/s. This matches approximately VPAM 6 to VPAM 7 [1][3].

V. Disadvantages of actual UHMWPE combat helmets

A. Back-face Deformation

Back-face deformation is one of the main problems of the actual UHMWPE combat helmets. On the one hand, the material has very good attributes against bullet penetration. On the other hand, the energy of the bullet is not well dispersed. In order to understand the back-face deformation, it is vital to understand the behavior of the fiber after an impact. Two waves occur: a transversal and a longitudinal wave (see Figure 3). The longitudinal wave moves along the fiber. During this movement, the fiber is stretched and constricted. The transversal wave moves in the direction of the projectile path. Due to the stretched fiber and the transversal wave the material suffers a deformation in the direction of the projectile. This leads to the so-called back-face deformation, the material indent and the residual energy appeals on the head [4]. For German police helmets, the residual energy has a maximum tolerance limit of 25 Joule [6]. The residual energy could lead to possible head injuries like long linear skull fractures or closed head brain trauma. At the moment, it is unclear whether the injuries occur from the deforming of the helmet onto the head or from acceleration loads transmitted through the helmet padding to the head.

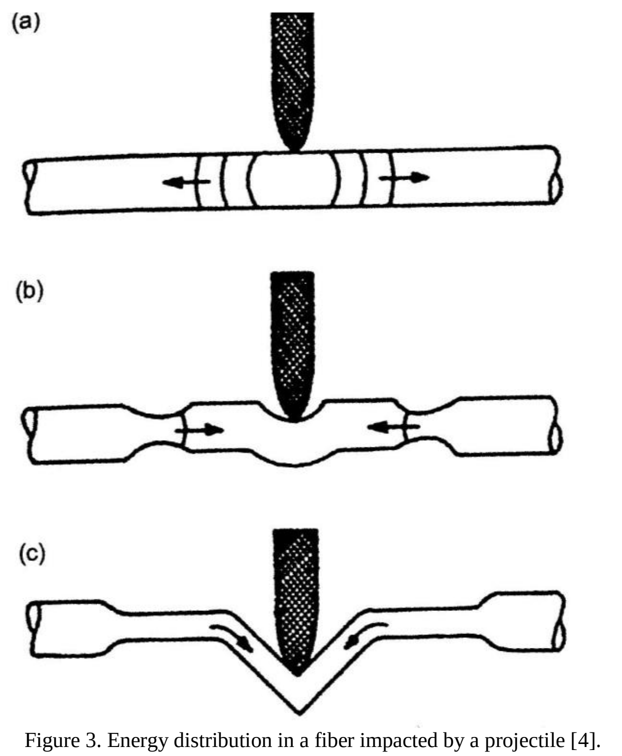

Figure 3. Energy distribution in a fiber impacted by a projectile [4].

In addition, the test methodology with clay to display back-face deformation is not totally linked to head injuries. The human skull behavior in such situations is inadequately represented in the actual test methodology with clay. Especially in the area of back-face deformation there is a lot of potential for necessary improvements [1].

B. Blunt impacts

Moreover, the current generation of UHMWPE combat helmets have deficits with blunt impacts. The current combat helmets can only absorb impacts with a velocity of 3 m/s or 45 J drop energy [3]. As mentioned earlier, common blunt traumas occur with a velocity of 6.1 m/s. In fact, blunt traumas occur especially in non-combat and training situations. Therefore, there needs to be an improvement, because most of the time the wearer of the helmet is in such a situation [1].

VI. Combat Helmet as Modular Headgear System

Combat helmets will evolve from a device only used for protection to a multi useable platform to increase the survivability and efficiency of the wearer. This includes basic attachments like active ear protection, flashlights or counter weights to provide a stable weight balance. Moreover, the helmet platform can be used to increase the leading ability of the group by adding integrated voice radio, a head up displays with important mission information or health sensors to monitor the group vital functions. This would increase the situational awareness of the group leader and would lead to an overall increase of safety during missions. Furthermore, the combat value of every solider or policeman can be increased by adding feeder plates for night vision, the ability to wear protective masks against warfare agent or attaching standardized rails like MIL-STD 1913. Of course, the possibilities are limited due to the weight the wearer can handle over the duration of the mission. So, if the combat helmet itself weight as little as possible, there are more possibilities for attachments and this leads to earlier mentioned advantages [1].

VII. Aim of the Project

First of all, the aim is to create a UHMWPE combat helmet, which meets the regulations of the police institute of the German police academy in Muenster, this regulation is based on the technical directive “System Ballistic Helmet” (Technische Richtlinie “Gesamtsystem Ballistischer Schutzhelm”) from May 2010 [2]. The use test standards are the VPAM “APR 2006” (Allgemeine Prüfrichtlinie 2006; Engl.: general test guideline 2006) and VPAM “HVN 2009” (Durchschusshemmender Helm mit Visier und Nackenschutz 2009; Engl.: bullet-resistant helmet with visor and neck protection 2009).

A. Threats

The main focus of the research is on the ballistic attributes of the helmet. Therefore, the helmet has to provide protection against soft-core projectiles 9mmx19 fired by small arms and machine pistols. This is comparable to VPAM 3. Furthermore, the aim is to meet the regulations of VPAM 4 to compete with the current generation of titanium helmets and provide a state-of-the-art alternative [5]. The mentioned titan helmet, which is actually used by the state of Baden Wuerttemberg, is the “Hoplit” model by Ulbrichts Witwe GmbH (see Figure 4). As mentioned, earlier protection against blunt trauma is also a challenge for combat helmets. The residual energy has to be lower than 25 Joule [1].

B. Constructional Problems

At the moment, the material has a reliable protection against projectile penetration. Additionally, a possible helmet shape provides a reliable protection. It has to be verified in which areas the protection is effective. Especially near the edges of the calotte, it is possible that the protection efficiency is much lower compared to the central areas. The actual titanium helmets have an efficiency distance of 10 mm to the edges. All in all, these helmets provide an effective protection area of 90% [6]. As with aramid helmets, which have a much lower protective area, the fiber structure of the UHMWPE could also be a crucial point to provide a protection area as big as titanium helmets [5]. Moreover, it is important to determine the optimal shape and configuration in which the UHMWPE tape is used. The goal is to use fibers, which are as long as possible in order to retain the good physical properties. This is difficult to achieve with a spherical object and rectangular tapes.

C. Possible Solutions

The main problem is back-face deformation. The residual energy dispensation of the material is too low in the current configuration. Now three possibilities to increase the dispensation have to be tested. Varying the direction of the material layers may mitigate the deformation. This has to be balanced between penetration and deformation of the material. The best penetration protection is provided when the layers are rotated by 90 degrees. Another idea is to use energy-absorbing materials under the calotte and as helm pads to reduce the residual energy. So, this means to integrate strictly the inlay into the helmet.

Figure 4. “Hoplit F” by Ulbrichts Witwe GmbH [6]

Another possibility is to use two calottes, the first one as a ballistic shell and the second one as a shell to disperse the residual energy and to add absorbing material between the shells. The next step would be to precise the ideas and test their efficiency. After this, a combination of ideas could reduce the residual energy to a value lower than 25 Joule. Finally, the aim is to meet the regulations of VPAM 3 [1].

VIII. COMBAT HELMT DEVELOPMENT

Before the development started, a progress plan was created. The plan is structured as follows: The first step is a detailed research concerning the material involved. This includes a literature research about failure behavior and material properties (a detailed report about this topic is readable [8]) and studies about material behavior during the processing, which is mentioned in this article. The next step will be the production of a prototype, made with different construction methods to find an optimal configuration. Also, the optimal hardening process parameters need to be found. Finally, these prototypes have to be tested on the basis of the VPAM HVN 2009 standards.

A. Used Material

The UHMWPE, which is used for this research is Dyneema® HB26. It is shipped in tape shape and as such, the matrix and fiber have already been combined to a fiber composite material. This material is ideal for body armor due to its low weight (density: 15.9 g/cm^3) and high tenacity of 37 g/d [7]. The tape has a bidirectional fiber structure with four layers of fibers (see Figure 5). This means that the tape has two layers in horizontal and two layers in vertical direction. That is an important fact, because the physical properties depend on the supported fiber length in the significant direction and has to be considered during the construction. Another crucial point is low temperature stability. The operating temperature range must be lower than 80°C, otherwise the material behavior might change [7].

Figure 5. Damaged Dyneema® HB26 tape. Layer-, matrix- and bidirectional fiber structure is visible.

B. Pre-processing

The tape has to be cut into the needed pieces for the construction. Because of the fiber structure of the material, a contactless cutting method is advantageous. Therefore, a laser cutter is used. It uses a CO_2 laser due to the inorganic material, which is processed. Due to the limited working surface of the laser cutter, the tape has to be cut into semi-finished material, which fits into the laser cutter. Therefore, a special fiber scissor is used for a preferably tear free cutting. The laser cutter has three main parameters influencing the cutting result: power, velocity and frequency. Following recommendations of the manufacturer of the laser cutter the settings are chosen as follows: the power is set to 120 W, the frequency is set to 1000 Hz and a 1.5’’ lens is used. Now, only the velocity needs to be determined. The cutting results are evaluated in several experiments. Bulging caused by the lead in heat, an optic evaluation of the cut and visible damages are compared at various velocities. Bulging turned out to be an important figure. That is because in lower velocities, the heat input leads to a bead nearly twice as thick as the thickness of the Dyneema® HB26 (original thickness 0.35 mm) (see Table I). The same applies to high velocities. High beads are an indication that the edges have been melted away and causes problems with geometrical accuracy. A velocity of 0.036 m/s seems to be optimal cutting setting to cut one layer of Dyneema® HB26 (see Table II). With this velocity, 0.5 mm of material from edge is melted away. This has to be regarded during the construction of the component. In order to increase productivity, experiments were made with five layers of material taped together being cut at once (see Figure 6). The velocity and focus point of the laser were changed throughout the experiment (see Table III). The best result is achieved with a velocity of 0.011 m/s and a focus point on the first layer leads to an acceptable cut.

TABLE I. COMPARISON OF THE CUT EVALUATION

Velocity [m/s]	Number	Bulging [mm]	Optic Evaluation	Damage
0.027	1	0.65	Bead	Fiber tearing
	2	0.68	Bead	No
0.032	1	0.58	Bead	No
	2	0.59	Bead	No
0.036	1	0.48	Even Edge	No
	2	0.48	Even Edge	No
0.044	1	0.52	Even Edge	No
	2	0.51	Even Edge	No
0.053	1	0.53	Even Edge	No
	2	0.56	Fringed Edge	No
0.062	1	0.59	Fringed Edge	No
	2	0.60	Bead	No
0.071	1	0.68	Bead	No
	2	0.63	Bead	No

TABLE II. OPTIMAL CUTTING PARAMETER OF DYNEEMA® HB26

Parameter	Value
Material	Dyneema® HB26
Power	120 W
Frequency	1000 Hz
Velocity	0.036 m/s

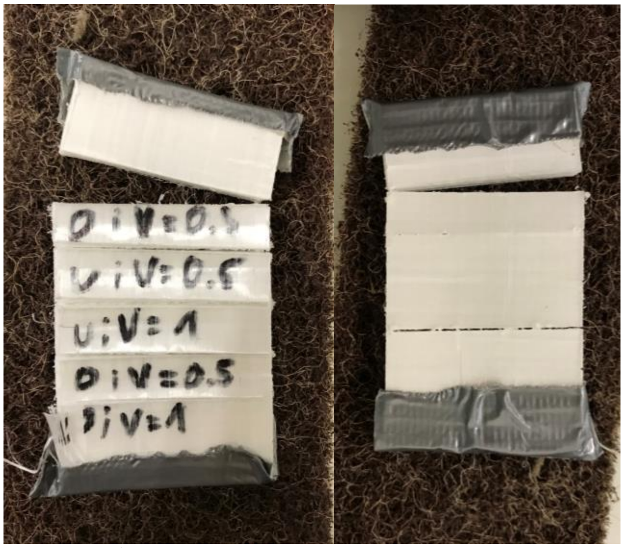

Figure 6. Left: Dyneema HB26 cluster with parameter labeling. Right: Reverse side of the cluster.

TABLE III. EVALUATION OF CUTTING PARAMETERS OF DYNEEMA® HB26 FIVE LAYER CLUSTER

Focus Point	Velocity [m/s]	Successful Cut
Upper Layer	0.011	Yes
Bottom Layer	0.018	No
Bottom Layer	0.036	No
Upper Layer	0.018	No
Upper Layer	0.036	No

C. *Post-processing*

After the hardening-process, the edges of the plates are often irregular. It is advantageous to achieve a clear edge to prevent fiber tearing and damages. The test plates have a thickness of twenty layers and are hardened. In the evaluation, the velocity, frequency, focus point, lens and repetitions are variable. However, multiple settings are tested and evaluated to the following criteria: geometrical accuracy, damages, bead and cleanliness of the cut. Finally, the settings displayed in Table IV produce an optimal cutting result (see Figure 7).

TABLE IV. OPTIMAL CUTTING PARAMETER OF HARDENED 20 LAYER DYNEEMA® HB26

Parameter	Value
Velocity	0.011 m/s
Frequency	1000 Hz
Focus Point	Upper Layer
Lens	1.5’’
Repetitions	5

Figure 7. Hardened 20 layers Dyneema® HB26 plate after post-processing.

IX. CONCLUSION AND FUTURE WORK

There are three main risks for ground forces: the main blast, blunt trauma and ballistic threats. Especially ballistic threats are challenging the UHMWPE helmets because of a high amount of residual energy. This leads to back-face deformation, which can result in live risking head injuries. In addition, this characteristic of injuries appears with blunt traumas. Some of the mentioned ideas could also lower the risk of blunt traumas even if the main challenge is to reduce back-face deformation. Another advantage of lighter helmets is, in addition to more comfort, the ability as a multi role carrier for attachments and a higher acceptance on the part of wearer. This ability could improve the survivability and efficiency of the wearer. Nevertheless, the focus is to reduce back-face deformation to meet the regulations of VPAM 3. Possible ideas are to verify the direction of the layers, using energy-absorbing materials for the helmet inlay or using two decoupled shells with energy absorbing materials in between. Therefore, a combination or balance between the mentioned ideas is necessary. Now, basic information about the material used exists and can be used to develop and build a prototype helmet. The next step is to evaluate how the prototype helmet can be constructed with possible solutions integrated as mentioned in Section VII/C. After that, ballistic tests are necessary to get an overview of the efficiency and how practical the solutions are. Especially the findings relating to the test methodology of the Review of Department of Defense Test Protocols for Combat Helmets [3] could be implemented into the test cycle. Findings mentioned in Section VIII are also usable for every future project with Dyneema® and represent an important first step. However, this should encourage further research of the hardening process to achieve better results in the future. To conclude, back-face deformation is current the main problem of UHMWPE helmets due to the residual energy transmitted through the inlay. As mentioned in Section V, also, the test methodology, to investigate the relation between back-face deformation and head injuries, has to be beheld and then maybe adjusted.

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