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Contemporary Personal Ballistic Protection (PBP)

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Abstract

The review concerns existing contemporary protective equipment and their components serving against ballistic and non-ballistic threats of different sorts. The main focus, however, is on the personal ballistic protection (PBP) based on textile components and their role in the protective elements. Soft ballistic protections are crucial Soft ballistic protections are crucial elements of PBP, for example in military and law enforcements. Although the subject of PBP was limited in this chapter to soft ballistic protection, other elements, e.g. hard ballistic protection, stab-resistant vests, dual threat, so-called in-conjunction protective elements, modern helmets, were also mentioned in this chapter to demonstrate positioning of the soft ballistic protection and other elements in the global personal protection approach. Apart from it, the chapter contains selected information concerning high-performance polymers and fibres as well as a brief notes about their application in protective panels being basic elements of any protective element. The final remarks concern the most up-to-date approach in relation to ballistic protection, which is immersing high-performance fibres into non-Newtonian liquid substances having the ability of ordering their chemical particles and changing into a high concentration and high segregation lattice under the influence of kinetic energy impact.

Keywords: personal ballistic protection, soft body armour, hard body armour, dual threat, stab-resistant vests, bullet-resistant vests, protective panels, high-performance fibres

1. Introduction

This chapter provides selected and the most up-to-date information concerning personal ballistic protection (PBP). The reason for writing this chapter is that the world of textiles is developing rapidly and this development includes technical textiles, protective clothing and equipment. Therefore, the novelty of these aspects is worth presenting. In addition, some

selected and spectacular historical facts are presented here and they concern inventions, decorations, extreme cases and lack of ergonomic wear comfort (e.g. medieval armour). Thus, inventions like, for instance, armours dating back to pre-conquest Mexico—e.g. quilted cotton jackets soaked in brine as a support for overlapping plates of hardwood or coconut fibres armour against shark's teeth—will not be mentioned here, although these inventions are very interesting from the textile engineer's point of view.

Ballistics is the science of mechanics which concerns the movement and effects of different projectiles, especially bullets, on different objects. Therefore, protection against any projectile can be termed a ballistic protection. As there are different types of ballistic-resistant materials, this chapter will be totally devoted to PBP, which can be defined as a unique, close-to-body human protection. A common mistake or a mental shortcut concerning the term 'bulletproof materials' is the concept of bulletproof vests. In reality, PBP materials are not bulletproof, but they are bullet resistant. This means that ballistic-protective equipment utilized to protect against any ballistic danger is not completely immune to different dangers, missiles, projectiles, etc.; for example, retarding and/or mitigating the speed of dangerous objects with potentially penetrating abilities until the ballistic protection can stop it.

In addition to a concise history of PBP and its existence and evolution over the centuries, this chapter will present characteristics of the most contemporary PBPs, their composition and designs, including soft body armours, some hard body armours, helmets with concise information concerning protection from stabbing and sharp edges penetration. Additionally, different types of contemporary PBP will be presented, e.g. law enforcement, military personal protection, including sappers and K9 protection for dogs. The role of ballistics, types of guns and most of all PBP requirements, standardization and classification for contemporary PBP is also discussed in this chapter. The key market players are mentioned several times when needed. Some additional and concise facts are mentioned to reach the knowledge of the reader, e.g. future trends, especially for so-called liquid armour.

2. History of body protection

2.1. Early stage

The history of PBP is a history of conflicts between humans mixed with developments of weapons and materials utilized for protection. The first weapon was a human fist, a kick, a stone or a stick. Later, different bludgeon-like objects were developed for attack and self-protection. Due to its historical connotations, the club weapon is strongly associated with primitive cultures of the caveman era or Neanderthal era; however, this weapon is still in use but it is now called a baseball bat [1]. Thus, the first sorts of personal protections against blunt trauma, slashing, bites or stabbing can be dated back to beginning of humankind. These were made of different kinds of animal skins and furs [2–7]. The subject literature often mentions the skin of oxen as a source of the precious leather, which was utilized as armour by the Mongol army as early as the thirteenth century BC, a detailed description of which is given in an historic review [8]. Another important animal skin came from rhinoceros, which was utilized in China

in the eleventh century BC [9], and from wild buffalo; these materials protected the torsos of the warriors. It seems that aspects of the ergonomics of personal protections were found to be important at that time. In order to increase the mobility of the warriors, some armies utilized textiles made of silk or linen. Linen was a very popular material, so there is nothing unusual in the fact that it was utilized as a component or a main raw material for linothorax. This element was a type of upper body armour used by the ancient Greeks. Different historical sources mention flax materials and associate weavers as producers of a base for an armour for the Greek army. In the early fourth century BC, the Athenian army underwent some military reforms, including the replacement of heavier bronze or chain mail body armour with linen corselets. As mentioned above, the key factor influencing changes was increasing the mobility of the soldiers by giving them armour that was 'light but protected the body equally well', in addition to reducing the size of the shield carried [3, 10, 11].

Some contemporarily reconstructed 10 mm composites were composed of 19 layers of low mass surface linen woven fabrics, while others achieved the same thickness using only 10 layers of much thicker linen. When it came to flexibility and resistance to stress, the performances of the 10-mm thick 19-layer and 10-layer pieces demonstrated very similar mechanical deformation parameters [3].

2.2. Fancy metal armour

Very often different armies around the globe utilized cloth garments with some metal (bronze) plates or scales attached to them. This form of protection was popular among the Assyrian (900–600 BC) and later Greek armies. There were further Gallic (eighth and ninth centuries), English (eighth century) and Frankish (ninth century) developments of this style.

The armour worn by a soldier presented in **Figure 1** is a perfect example of scales armour combining small, usually iron plates. Another historical source [12] suggested a simplified differentiation between metal elements attached to the system. According to this study, the

Figure 1. English soldier, eighth century; source: Grafton [6]. Arms and Armour: A Pictorial Archive from Nineteenth-Century Sources (Dover Pictorial Archive), Dover Publications, New York, USA, 1995.

external small plate armours are divided into three categories: lamellar, scale and an undefined category. When utilized to protect a torso, scale armour overlaps downwards and is predominantly mounted on a continuous substrate, usually of textile or leather. The second type is lamellar armour, where lamels overlap upwards and are connected continuously to the substrate, but are connected with each other by different cords.

Another very important innovation in armour was a mail armour (or chain mail). The exact invention moment and its place is unknown, but it was widely utilized in Europe in the Middle Ages quickly spread and was further developed and transformed by different nations, e.g. France, England and Germany. As mentioned before in the text of this chapter, the roles that were assigned to armour in the Middle Ages were protection and decoration but also presentation of social status and intimidation of the enemy. The examples of such types of armours are presented in **Figure 2**(**a**, **b** and **c**). The chain mail is noticeable on the arm of the silhouette (b) in **Figure 2**.

Together with the development of firearms, suitable protective armour was developed to absorb the impact of firearms. As a consequence, body armours (including helmets) were made of different types of metals and their mass became very high. In fact, the period from the fifteenth to sixteenth century abounds in the greatest amount of very sophisticated, decorative armour for different level soldiers and noblemen in Europe.

A simplified version of protection is Polish Hussar top armour and a helmet, as presented in **Figure 3**. It was made of steel, iron, brass and leather. It is less decorative and the elements of tiles protecting the arms and shoulders suggest that requirements for increased mobility of the wearer were taken into consideration when designing this armour.
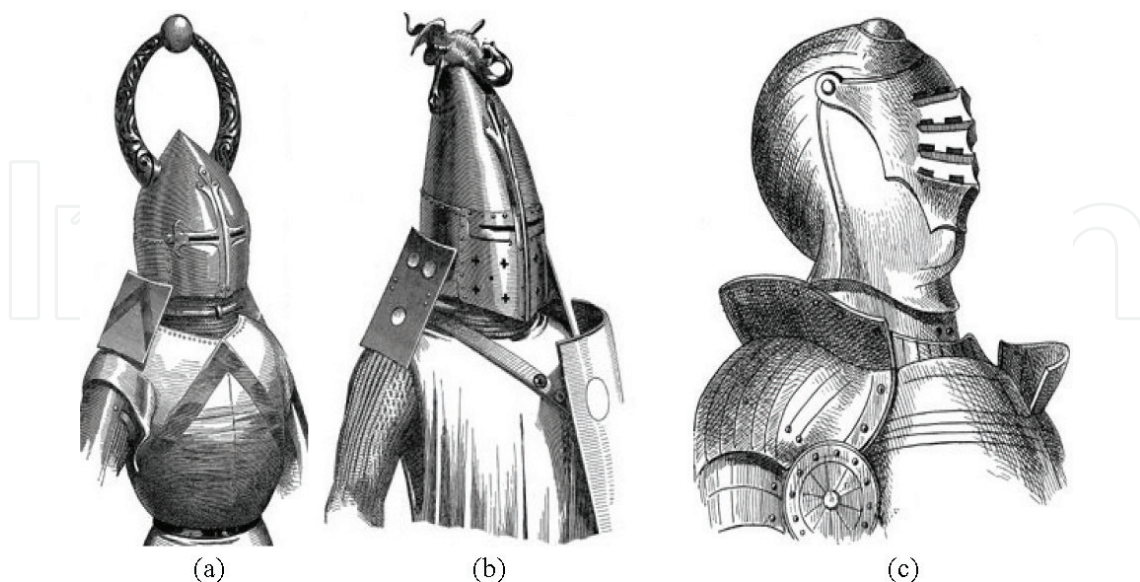

(a)   (b)   (c)

Figure 2. The armours (a) and (b) date back to the thirteenth century and (c) to the fourteenth century; they all come from France, region and hierarchy unknown; source: Grafton [6]. Arms and Armour: A Pictorial Archive from Nineteenth-Century Sources (Dover Pictorial Archive), Dover Publications, New York, USA, 1995.

Figure 3. Half armour for a Polish Hussar, dating back to 1683–1700. Made of steel, iron, brass and leather, presented at an exposition in The Art Institute of Chicago, Chicago, Illinois, USA; source: own photo, archives of the author.

Independent of the fact that further development of armour was going in the direction of increasing mobility and visibility, the armours of the nobles were still very decorative, thick, extremely expensive and also very heavy.

2.3. Japanese input

Japanese armour was also highly variated; the scale of its decorativeness depended on the position occupied by the warrior. The full armour set was worn only by the emperor, by a shogun (a military chef in the twelfth century; later the noble/the most skilled soldier), by a samurai who was a higher class swordsman or by the soldiers (but this armour was very heavy and uncomfortable). Up to the thirteenth century, there were two distinct types of armour: the *yoroi*, a heavy, box-like and very ornate and expensive style for mounted samurai and the *do-maru*, a simple suit of armour for the regular foot soldier, which was wrapped around the body of the soldier. Both were constructed from small metal plates connected together using leather elements (stripes). The sets of plates were fixed with silk cords to make a light but resilient armour plate. With time, mainly during the fourteenth century, samurai decided to adopt and adapt the *do-maru* as it was much lighter and more convenient for fighting on the battlefield. The more demanding battle conditions of the fifteenth and sixteenth centuries for samurai forced armour producers to reduce the mass and improve overall comfort of wear [7] (**Figure 4**).

It is very interesting to discover that Japanese shin guards called *suneate* were something even more than the inspiration for contemporary sport shin guards. In the Momoyama period of 1568–1600, armour craftsmanship reached a summit of excellence in providing the samurai with a suit of armour that would allow him to perform movements as freely as possible while providing him with the maximum protection against arrow, blade and ball. In this period of time, shin guards consisted of a number of vertical metal plates joined by chain mail on a cloth backing, with a leather patch on the inside of each to prevent rubbing against the stirrup
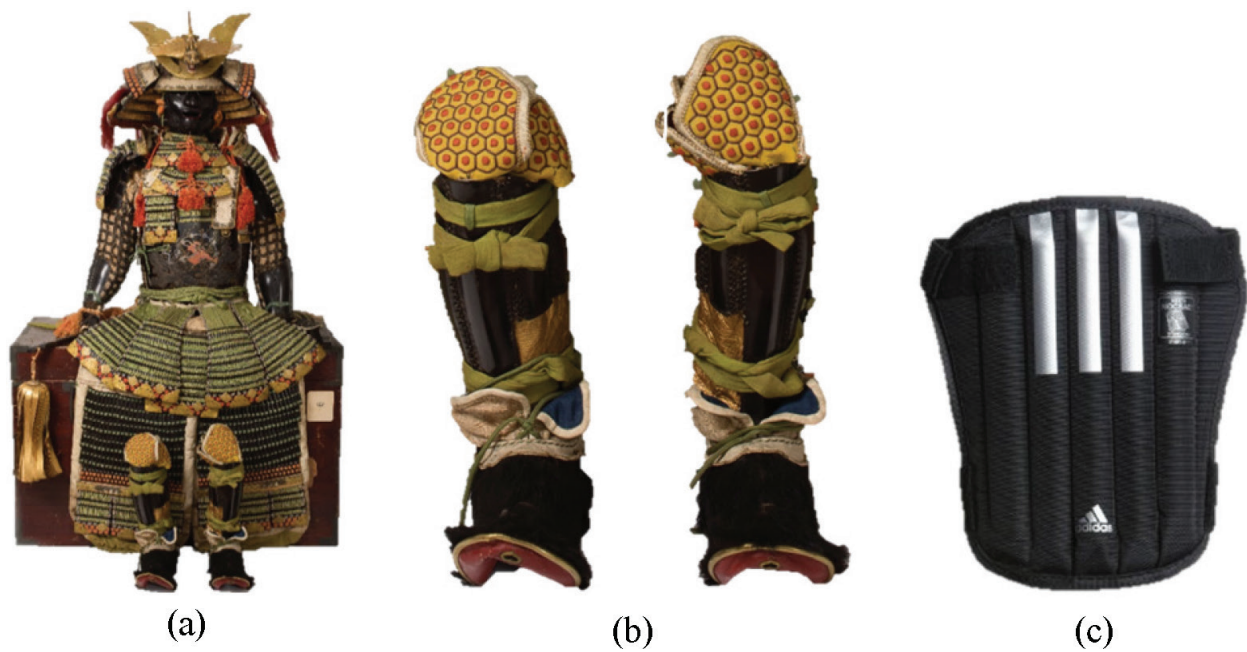
Figure 4. (a) Samurai armour, Edo period, eighteenth century: Kabuto bachi signed 'Masuda Myōchin Minbu Ki no Munesada Saku' and dated February 1757. This samurai armour has the kamon of the Inaba family. Kamon is a Japanese symbol used to decorate, identify and distinguish an individual or a family (source of (a) and (b): Giuseppe Piva Japanese Art, Milan, Italy; for more information see http://www.giuseppepiva.com/en/services) [13]; (b) shin protectors of a samurai armour from (a); (c) a contemporary football shin guard by Adidas; source: http://www.soccershoo.com/product/adidas-11-anatomic-lite-shinpads-x-large/[14].

when riding a horse [7]. A contemporary shin guard has a very similar construction, having a five-stick construction in the protection area to absorb blows. This construction allows the distribution of the impact force along the tibia and to the lateral muscle [15].

2.4. Armour improvements and the dusk of knighthood

There has been no special consistency in the use of armour over the centuries; however, it is believed that the use of different armours can be attributed to economic and technical reasons (e.g. external conditions, access to resources, lifestyle, fashions and a constant need not only for improvement in wear comfort but also for improvement in protective abilities of the armours due to the increasingly lethal potential of weapons). Different forms of cuirasses and plates, with reinforced or not reinforced coats, remained in use throughout the fourteenth and fifteenth centuries. In parallel and later, breastplates and backplates became popular, which covered the chest from the lower neck to just below the rib cage. They were made of steel, which was a relatively new development in the fourteenth century. The thickness of the steel shield varied between 1 and 2.5 mm, depending on the need for protection [16]. During the seventeenth century, the development of heavier, thicker plates to stop projectile-like missiles from guns offered an armour that was plain but functioned sufficiently well [16].

Overall, one may conclude that knights were wearing better and better protective equipment and any introduced improvements increased wear comfort and ergonomic requirements. However, armour was expensive and many young, prospective knights would need to either

gain money from tournaments or capture armour in battle. Around the seventeenth century, the presence of knights became less important as the whole concept of army organization and troops had changed. Mastering horsemanship and swordplay remained important in the eighteenth and nineteenth centuries, until the mechanized warfare of World War I made it redundant [16].

2.5. World War I

At the very beginning of World War I, very few armies were equipped with any form of body protection. Due to a huge number of casualties, the French Army introduced a modernized protective helmet. Starting in 1915, body armour was utilized on the battlefield, but only in a limited capacity. The equipment consisted of steep plates giving protection from shrapnel [4]. This single-shot French weapon—the same as that mounted on the FT-17 Renault tank—could fire a small explosive shell which was able to pierce ¾ inch of armour plate at 2500 yards (2286 m) and it proved to be especially effective at suppressing snipers and machine guns [17]. The German Army introduced silicon–nickel breastplates in May 1917 for its soldiers. Later, the British Army offered the highest variety of protection to their soldiers and the most interesting ones were the 'Best Body Shield' and 'Portobank' armoured waistcoats. An average level of protection and a low mass burden was provided by Berkeley's Flexible Armour Guard, the Franco-British Cuirass and Wilkinson's Safety Jacket (mass of about 3 lbs). The British Munitions Inventions Board conducted some experiments with textile materials, e.g. kapok, flax, cotton, sisal, hemp and silk. The idea behind the work was to slow and trap projectiles in the textile materials. The studies focused on silk, which turned out to be the most resistant of the tested fibres. The armour made of silk gave similar protection as a shield made of manganese steel.

2.6. World War II—Flak jacket development

One of the greatest body protections was the Medical Research Council (MRC) Body Armour, which consisted of three separate 1-mm thick steel plates, weighing a total of 1.1 kg to protect the heart, main vessels and lungs (first version); lungs, liver, parts of the spine (second version) and abdomen (third version). This armour was made to be comfortable and it could withstand a 0.38 calibre pistol bullet at 4.5 m and 0.303 calibre bullet at 640 m. MRC was introduced by the British Army in 1941. It turned out that this armour was far from ideal. Not only was it difficult to perform rapid movements while wearing it, but it caused wounds on the body. Two other types of body armour invented by the British Army and consequently tested by the American Army—the so-called the Armourette and the Wisbrod Armoured Vest—were characterized as increasing the load on the soldier, decreasing overall mobility and efficiency; therefore, the advantages of wearing this armour were at a minimum level [4].

After an analysis of the wounds of the soldiers in the US Air Force, it turned out that about 70% were due to low velocity missiles, namely 'flak' fragments. The term flak refers to anti-aircraft guns operated during World War II by the German **Fluga**bwehr**k**anone. The flak-protective vest, produced firstly in the United Kingdom and then in the United States, was known as the Flyer's Vest M1 and its modification was known as M2 (only the front of this

version was armoured) [4]. Both versions weighed around 3.6 kg. They were standardized in October 1943 in the United States and they initially used cotton covering fabric, but changed to ballistic nylon by DuPont over the next few years. Many other modifications were made, standardized and propagated among soldiers, e.g. M6–M8 [4].

2.7. Further developments

Until 1952, numerous different body armours were designed and redesigned, including the concept of adding 12 layers of nylon fabric to increase the flexibility of the body protection (so-called M-1951 body armour). During the Vietnam War, M-1955 was issued and propagated among soldiers. M69, which contained a ballistic nylon filling covered by waterproof vinyl plastic, was issued at a later point in the conflict. Twelve layers of ballistic nylon fabric protected the front and 10 layers protected the back of the soldiers. At this point in time, zippers of Velcro were already in use to close vests; the average mass was 4 kg and the cost was 35 USD [4].

In 1962, studies concerning the hardening of armour were conducted and further development concerning an enamel layer that could make the armour layer harder and more resistant continued under the title Hard Face Composite armour in the Goodyear Aerospace Corporation, Ohio, US. The performance of armour containing a ceramic front and glass-reinforced plastic (GRP) at the back was proven against small round projectiles. At present, the term glass fibre reinforced plastic (GFRP) is commonly utilized in composite related terminology, commonly referred to as 'fibreglass'; these reinforcements are made of high tensile strength glass fibres [18]. After 1965, body armour classified and standardized in the United States utilized three types of ceramics as protection, namely aluminium oxide (Al_2O_3; in the US Army use), silicon carbide (SiC) and boron carbide (B_4C; Navy, Air Force and Marines). These ceramic plates were introduced into the textile covers of the vests as monolithic plates [4, 18].

2.8. Post-Kevlar® invention era

One of the most important inventions of the twentieth century, apart from computers or life-saving heart-lung machines, is a synthetic fibre from the group of aromatic polyamides [19]. Nowadays, it is known by the name Kevlar®. The polymer out of which the fibre was made was invented in 1964 by the chemist Mrs. Stephanie Kwolek who worked in a research lab at DuPont. DuPont was looking for chemical combinations that would make stronger fibres for fabrics. In the course of lab experimentation, Kwolek heated a newly mixed combination of substances [20]. The mixture presented unexpected features. The new era of personal body protection had begun.

The initial tests performed on the fabrics made of Kevlar® proved its ability to stop a wide range of projectiles. The next stage was to elaborate a new set of bullet-resistant vests for law enforcement. In the course of these experiments, five plain weave fabrics woven from Kevlar® 29 yarns of 1000 denier (about 111 tex) were tested and turned out to be the most bullet resistant. Soon, it was discovered that this amount of layers could stop some of the projectiles, but could not prevent non-lethal injuries, which are nowadays called blunt trauma. A great number of modifications to the protective set of fabrics, as well as the design of the protection itself, were introduced. One of the most meaningful was the personal armour system for

ground troops (PASGT) weighing 4.5 kg (medium size). PASGT was made of Kevlar® and this abbreviation refers to both vests and helmets[1] made of Kevlar®. These were utilized by all military services from the mid-1980s to around the middle of the last decade [4, 19, 21].

3. Existing high-performance fibres for ballistic protection

1. **Arom**atic polyam**ides**, also known as **Aramids**, are chemical, man-made, synthetic polymers utilized for production of flame retardant and ballistic protection fibres. Aramids belong to the polyamide (PA) group, together with aliphatic polyamides (e.g. Polyamide 6 or 6.6 (PA 6 and 6.6)) and Polyphthalamides, also known as polyamides with semi-aromatic chains, e.g. Polyamide 6T (PA 6T). A very specific aramid known as Kevlar® was commercialized by the Du Pont Company in 1972. The discovered substance was characterized as having a super-rigid molecular chain and a fibre made of it had an ultra-high modulus [19]. Kevlar® aramid fibre is based on poly(*p*-phenylene terephthalamide; PPD-T), one of the *para*-oriented aromatic polyamides that was obtained by S. Kwolek. PPD-T can be prepared in the frame of a *classical synthesis* based on a low temperature polycondensation of p-phenylene diamine (PPD) and terephthaloyl chloride (TCI) in a dialkyl amide solvent and other methods, e.g. direct polycondensation reaction [19, 22].

   Apart from well-known types of Kevlar®—Kevlar®, Kevlar® 29, Kevlar® 49, Kevlar® 68, Kevlar® 100, Kevlar® 119, Kevlar® 129 and Kevlar® 149—relatively novel varieties include Kevlar® AP (15% higher tensile strength than K-29) [23] and KM2 Plus fibre [24] with enhanced ballistic resistance for armour applications [25]. **Table 1** presents a comparison of some high-performance fibres for ballistic purposes. Another type of aramid-based para-aramid fibre is Twaron® (a brand name of Teijin Aramid). It is a heat-resistant and strong synthetic fibre which was developed in the early 1970s by the Dutch company Akzo [26].

2. **Poly-p-phenylenebezobisoxazole (PBO)** is one of the polybenzoxazoles containing an aromatic heterocyclic ring. In 1994, Dow Chemicals, together with Toyobo, developed a new spinning technology that brought about the development of this substance. The process of polymerization of PBO takes place when polyphosphoric acid from 4,6-diamino-1,3-benzenediol dihydrochloride mixes with terephthalic acid. The fibre of PBO is made of highly oriented molecular chains, but its crystallite size is small compared to that of p-phenylene terephthalamide (PPTA), the component of para-aramid. PBO fibres consist of fully extended chains, like other high-modulus and high-strength fibres, but it also consists of highly oriented chains. Presently, there are two commercially available PBO-type fibres produced by Toyobo Co. Ltd. They are known in the market as ZYLON® AS (as spun) and ZYLON® HM (high modulus). Although nowadays the producer of these fibres does not clearly indicate their potential ballistic application on the website of the company, PBO-based fibre has about 1.6 times higher tensile strength than Kevlar, and these fibres are mentioned in the literature as ballistic fibres [27–34].

[1]Helmets are the topic of a separate sub-chapter; see **Helmets as elements of Personal Protection**.

3. **Ultra-high-molecular-weight polyethylene** (**UHMWPE, UHMW**) is a subset of the thermoplastic polyethylene. Also known as high-modulus polyethylene (HMPE) or high-performance polyethylene (HPPE), it has extremely long chains. UHMWPE is a type of polyolefin. It is made up of extremely long chains of polyethylene, which all align in the same direction. It derives its strength largely from the length of each individual molecule (chain). UHMWPE is synthesized from monomers of ethylene, which are bonded together to form the base polyethylene product. This type of fibre is produced from the polymer via the process of gel spinning. It is about 40% stronger than most aramid fibres. Due to these fibres' properties, they are predominantly utilized in ballistic protection. During the gel-spinning process, the fibre-forming polymer is dissolved in a solvent and spun through a spinneret. The polymer itself is in a gel-like state, which means it is only partially liquid. After spinning, the filaments have a highly oriented structure and the liquid crystals are aligned along the axis of the fibre. Currently, there are two major types of these fibres that are commercially available. They are produced by Honeywell and DSM under the names Spectra® [35] and Dyneema®, respectively [36]. Different series of these fibres have been established as their properties were modified during the production process, e.g. Spectra® 900, 1000 and 2000; Dyneema® SK25, SK60, SK65, SK71, SK75 and SK75. Both Spectra® and Dyneema® are utilized in ballistic protection products as they are characterized as having high-energy absorption and can dissipate the hit wave more easily compared with other existing ballistic fibres. These fibres are utilized for both soft and hard ballistic-protective products [2, 37].

4. **M5 Fibre (polyhydroquinone-diimidazopyridine) -** The synthesis of **poly[2, 6-diimidazo[4, 5-b4′,5′-e]pyridinylene-1,4-(2,5-dihydroxy)phenylene]polyhydroquinone-diimidazopyridine**) and the utilization of a conventional air gap wet-spinning of this solution in methanesulfonic acid led to the creation of a fibre known as M5 fibre which is a high-performance fibre originally developed by Akzo Nobel and currently produced by Magellan Systems International (Magellan) [28]. The crystal structure of this fibre features typical covalent bonding in the main chain direction, but it also features a hydrogen-bonded network in the lateral dimensions. The problems related to processing the fibre—and especially with obtaining an optimal crystal orientation and, as a consequence, optimal ultimate mechanical properties (e.g. average fibre strength was 4 GPa)—have led to modifications in this fibre's production process. These are expected to correspondingly increase ballistic impact performance [38].

5. **Endumax®** belongs to the group of fibres based on polyethylene. According to the specification given by Tejin, the producer of this fibre, Endumax®, can be produced in wide or thin tapes. Thus, one has a need of only 25% of the quantity of matrix material conventionally used to produce a UD or composite (compared with conventional thin multifilament yarns). Therefore, one makes some savings not only in terms of weight but also in terms of the amount of chemicals needed. Due to the material's high stiffness and shape at low matrix content, the pressure needed to produce a shaped anti-ballistic plate is approximately 60 bar—significantly lower than for other **UHMWPE** materials, which may require up to 200 bar pressure. When applied into shaped plates, this polymer retains its original form and protection performance levels, even if they have been exposed to temperatures and/or moisture levels above the normal working range (e.g. during storage) [39].

Commercial name of the fibre	Producer	Chemical substance	Density [g/cm³]	Tensile modulus [GPa]	Tensile strength [GPa]	Elongation at break [%]	Product forms and their applications	References
Kevlar® 29	DuPont[2]	poly-para-phenylene terephthalamide (PPTA)	1.44	71	2.9	3.6	Ballistic applications, ropes, cables, protective apparel such as cut-resistant gloves, helmets, vehicular armouring.	[2, 20, 28, 32, 40–43]
Kevlar® 49			1.45	78	3.4	3.3	High-modulus type used primarily in fibre optic cable, textile processing, plastic reinforcement, ropes, cables and composites for marine sporting goods and aerospace applications.	
Kevlar® KM2/KM2 Plus			1.44	82	3.9	3.3	Kevlar® KM2® and KM2® Plus technology help provide protection from select fragmentation and small arms threats. KM2® Plus represents the highest grade protective fibre for military use. Kevlar® KM2 is meant for helmets and vests for military and high-performing spall liners. Kevlar® KM2 Plus is a high tenacity, high toughness and finer denier fibre used in vests and helmets for both military and law enforcement officers	[2, 25, 28, 32, 40, 43]
Twaron®	Teijin	PPTA and poly-para-phenylenediamine (PPD)	1.44	70	3.2	3.3	High ballistic protection, lower weight, greater comfort and longer lifetimes, protects against penetration of bullets, and fragments as well as stabbing	[2, 20, 43–45]
Spectra 900	Honeywell	Ultra-high-molecular-weight polyethylene (UHMWPE)	0.97	2.4-3.5	2.4-3.5	4.0	Stronger than steel and 40% stronger than aramid fibre. Capable of withstanding high-load strain-rate velocities. Spectra® fibre, one of the world's strongest manmade fibres, is commonly used to produce bullet-resistant Spectra Shield® body and vehicle armour and helmets	[2, 20, 35, 37]
Dyneema® SK75/SK78 but Dyneema® different grades: HB212, HB210, HB80, HB56, etc. is meant for Hard Body Protection	DSM		0.97	109-132	3.3-3.9	3.0-4.0	Dyneema® Force Multiplier Technology can reduce the weight of armour by up to 20%. The result is exceptionally protective performance without compromising comfort, agility, or function. Comfortable protection against handguns, shrapnel and knives. Dyneema® is used in ballistic helmets, vests and shields. It is utilized in protective equipment to safeguard soldiers, law enforcement officers, commercial pilots and high-profile civilians. Grades of hard ballistic protections (inserts, helmets and shields) are HB212, HB210, HB80, HB56, HB50, HB26 and HB2, respectively, from the highest to the lowest performance and aerial density [g/m²] from 0.136 ± 0.005 up to 0.261 ± 0.005	[2, 20, 36]

Commercial name of the fibre	Producer	Chemical substance	Density [g/cm³]	Tensile modulus [GPa]	Tensile strength [GPa]	Elongation at break [%]	Product forms and their applications	References
M5	Magellan Systems International LLC; with DuPont starting from 2005	Polyhydroquinone-diimidazopyridine	1.70	271	3.9	1.4	Fibres are lighter and give more effective protection from different threats, including bullets, fragments, IEDs and mines, than other existing fibres. Potential future applications of the fibre include fragmentation vests and helmets, composites for use in-conjunction with ceramic materials for small arms protection and structural composites for vehicles and aircraft	[2, 20, 28, 29]
Zylon ® AS	Toyobo	Poly-phenylene benzobisoxazole (PBO)	1.54	5.8	180	3.5	Although Zylon is a high-performance fibre and was utilized in the past for ballistic purposes, the website of the producer of this fibre does not provide information about potential ballistic applications for this fibre	[2, 20, 27]
Zylon ® HM			1.56	5.8	270	2.5		
Endumax®	Teijin	Ultra-high-molecular weight-polyethylene (UHMWPE)	0.97	170	2.8	1.7	Endumax lightweight plates enable ballistic protection gear to meet requirements in terms of protection, flexibility and low weight. Protective unidirectionals (UDs) and composites (like insert plates), protective panels and helmets made from Endumax, have a very high degree of braking energy, resulting in a particularly high-stopping power for bullets and fragments. Endumax can be applied in both soft and hard body armour	[39, 46]

[1]Only selected fibers are presented in **Table 1**. If these are classified as soft body armour, it means that they are utilized predominantly in this application, but it does not exclude them from being applied elsewhere.

[2]DuPont, Honeywell and other companies offer a large number of different high-performance and high-modulus types of fibres and fabrics, e.g. Kevlar 68, Kevlar 100, Kevlar 119, Kevlar 129, Kevlar® XP™ [41], Kevlar Protera® Fabric Arc Flash Performance [42], S-900 family, S-1000 family. This technology, made from a high-toughness resin combined with Kevlar® KM2® Plus fibre, helps manufacturers provide a 20% decrease in helmet weight while maintaining the same performance. Kevlar® XP™ for hard armour provides a minimal back face deformation. Although the materials have exceptional mechanical properties, only very few of these materials are designated by their producers for ballistic protections.

Table 1. Comparison of typical high-performance fibres predesignated for ballistic purposes in soft body armour (fabrics, panels, composites)[1].

3.1. Ballistic structures

The high-performance yarns are collected together into a form of woven fabrics, knit structures and non-woven materials. These arrangements/structures allow the dissipation of bullet impact energy reasonably quickly. The essence of bullet-resistant materials is that when grouped together into panels (e.g. a specific/determined number of identical materials placed one onto another) and put into vests, they constitute bullet-resistant vests.

3.2. Action mechanism of the bullet-resistant vest

The ballistic performance of woven structures in the ballistic packet of the bullet-resistant armour depends strictly on the mechanical properties of yarns and fibres (type of high-strength fibre, type of weave, linear density of the yarn and weave density). In the case of woven fabrics utilized as a protective packet, the fabrics are woven densely in the form of plain weave. It was observed that the density of the yarns packed to form the weave for ballistic fabrics is the best from 0.6 up to 0.95 [2, 28, 43]. Below 0.6, fabrics are simply too loose to meet ballistic requirements and above 0.95 the yarns are tightly packed and can be damaged during the fabric production process. When hitting the surface of protection made of woven fabrics, projectiles cause a deformation of these fabrics that starts to spread the yarns apart. This takes place especially when the calibre of the bullet is small. In such a case, it can penetrate the fabric without or with very limited yarn damage. In case of larger calibres, the yarns tend to lock up the bullet in one of the inner layers, while the initial layers and yarns within them are damaged due to the bullets passing through them. The bullets are slowed down by the initial layers and the impact energy of the bullets reduces and is dissipated. In order to dissipate impact energy quickly and to offer the maximal protection, Unidirectional (UD) shields are used for both soft and hard panels, e.g., Dyneema®UD by DSM and Spectra®Shields by Honeywell. In Dyneema®UD, all the yarns (groups of filaments) are positioned parallel to each other, in the same plane, rather than being woven together. In UD configuration, the fibres of Dyneema®UD allow energy transmission from the place where the bullet strikes by energy distribution along the fibres much faster than in conventional woven fabrics. This is due to the fact that the absorption power of the yarn in woven fabrics is lost at the cross points of warps and wefts. It has been proven that instead of supporting the impact energy dissipation process, the cross points (or crossover points) rather hamper this process [2, 35, 36, 43]. Spectra Shield™ is not a woven material, but a thin, flexible ballistic composite made from layers of unidirectional fibres held in place by flexible resins. These Spectra fibres of a single layer are arranged in a way which does not allow them to cross each other. The fibres of the second layer are placed and held in a different direction compared with the fibres of the first layer, e.g. the fibres of the first layer are kept under 0° and the fibres of the second layer are kept under 90°, but all in the same plane. Then, both layers are sealed between two thin sheets of polyethylene film. A similar solution is applied in Twaron Unidirectional Laminate UD41—or those combining UD41 with other Twaron materials—and offers several advantages for engineering these modern ballistic-protective vests. They provide enhanced protection against bullets and fragments, as well as more comfort and excellent performance–weight ratios. Twaron UD41 is a unidirectional laminate suitable for soft body armour. Consisting of four plies of unidirectional Twaron fibre lines (plied in a 0°/90°/0°/90° configuration, as presented in **Figure 5**), it makes full
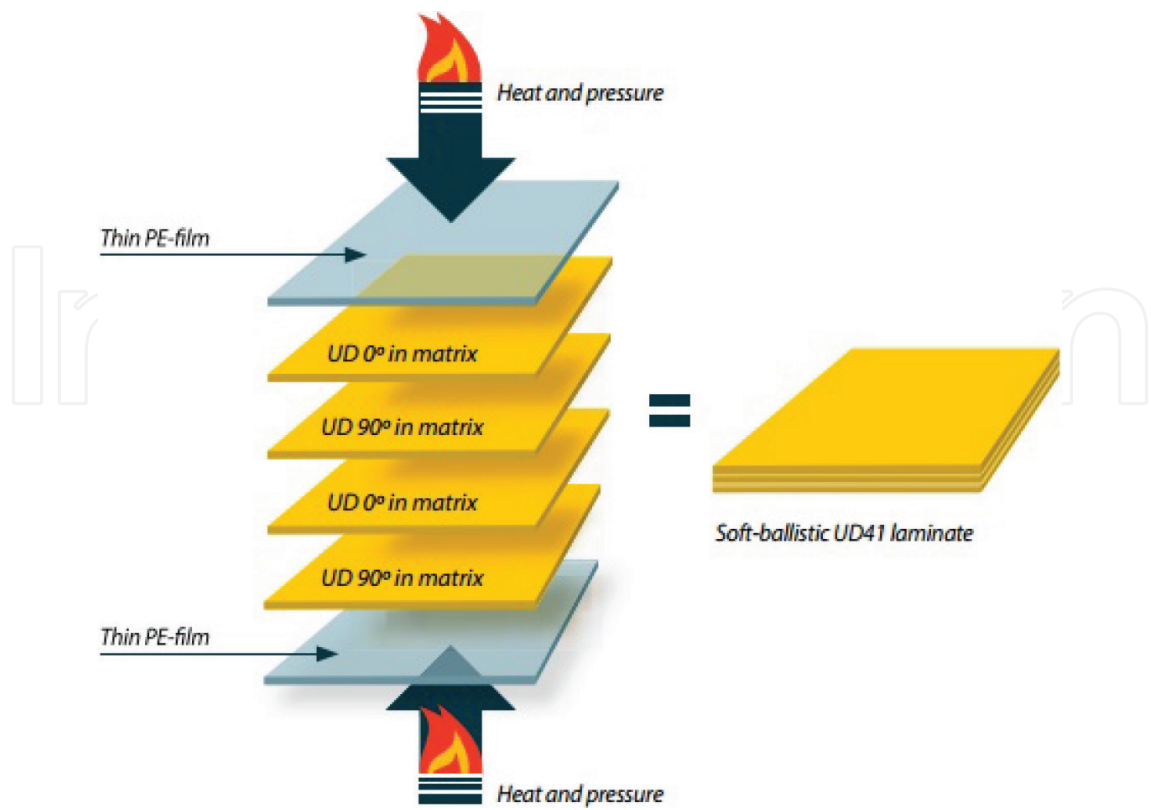
Figure 5. Schematic presentation of a single ballistic laminate UD41 by Tejin; PE stands for polyethylene; UD stands for unidirectional; source: Ballistics material handbook—Twaron by Teijin [http://www.teijinaramid.com/wp-content/uploads/2016/05/Teijin-Aramid-Ballistics-Material-Handbook.pdf].

use of Twaron's high-fibre tenacity and avoids the crimping of typical woven material. So-called smart UD technology aligns the parallel Twaron fibres in each layer, and each layer is constructed in a resin matrix. The top and bottom UD plies are then laminated to ensure maximum abrasion resistance [47].

Some examples of fabric and composite materials utilized for ballistic protection in soft armours are presented in **Figures 6–14**.
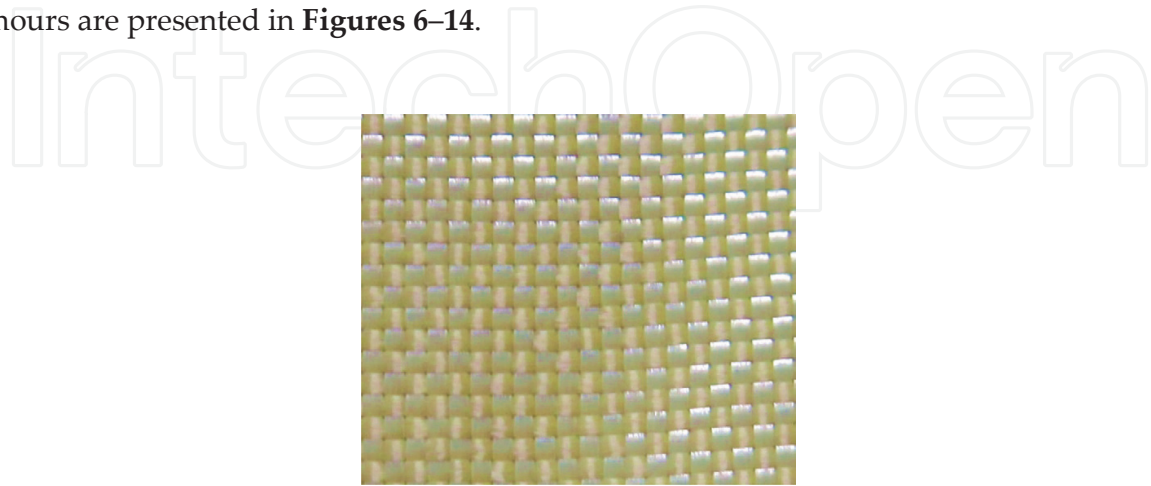

Figure 6. Plain weave fabric made of Kevlar 49® yarns by DuPont; source: author's own photo archives. Note: Plain weave single fabric; 85 warps/10 cm and 85 wefts/10 cm. Both warps and wefts are made of Kevlar. Total area density: 300 g/m². Thickness: 0.35 mm.

Figure 7. Ballistic panel Gold Shield® GV-2018 with Kevlar® by Honeywell; source: author's own photo archives. Note: The sample is composed of two panels and each of the panels consists of two layers. The first layer consists of sets of the parallel yarns positioned vertically (V) and the second layer contains the yarns positioned horizontally (H). Thus, the scheme of the sample construction is: (V + H) + (V + H). Total area density: 510 g/m². Thickness: 0.78 mm.
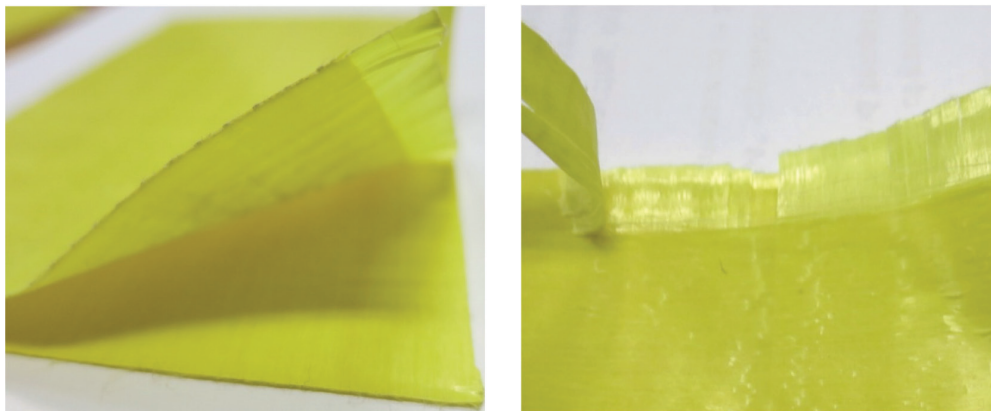

Figure 8. Ballistic panels Gold Shield® GV-2018 with Kevlar® by Honeywell. The sample is delaminated/stratified, showing two separate layers of a single panel with yarns positioned perpendicularly; source: author's own photo archives.

Figure 9. Ballistic panel Gold Shield® GN-2119 with Kevlar® by Honeywell; source: author's own photo archives. Note: Sample constitutes a single panel, made of two layers. The first layer consists of sets of the parallel yarns positioned vertically (V) and the second layer contains the yarns positioned horizontally (H). Thus, the scheme of the sample construction is: V + H. Total area density: 107 g/m². Thickness: 0.1 mm.
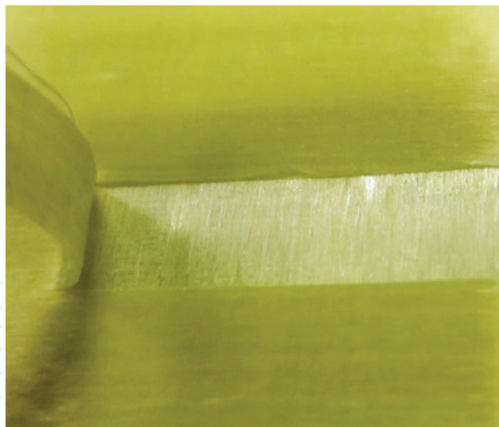
Figure 10. Ballistic panel Gold Shield® GN-2119 with Kevlar® by Honeywell. The sample is delaminated/stratified, showing two separate panels with yarns positions perpendicularly; source: author's own photo archives.

Figure 11. Ballistic panel Spectra Shield ® SR-1226 by Honeywell; source: author's own photo archives. Note: Sample is composed of two panels and each of the panels consists of two layers. The first layer consists of sets of the parallel yarns positioned vertically (V) and the second layer contains the parallel yarns positioned horizontally (H). Thus, the scheme of the sample construction is: (V + H) + (V + H). Total area density: 253 g/m². Thickness: 0.7 mm.

Figure 12. Ballistic panel Spectra Shield ® SR-1226 by Honeywell. The sample is delaminated/stratified, showing two panels with two layers each, and the yarns in each panel are positioned perpendicularly; source: author's own photo archives.
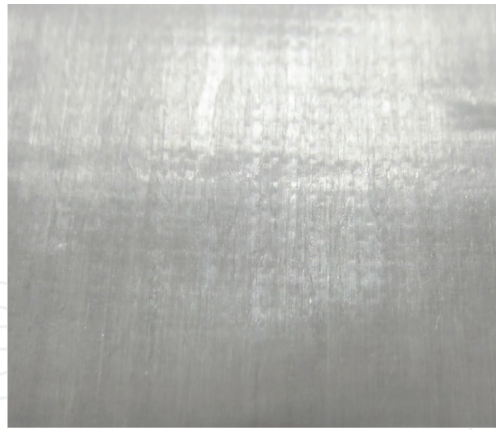
Figure 13. Ballistic panel Spectra Shield ® II SA-4144 panel by Honeywell; source: author's own photo archives. Note: From a distance, Spectra Shield® II SA—4144 is difficult to distinguish from Spectra Shield® SR-1226. The organoleptic assessment of the samples allows an easy verification. Spectra Shield® SR-1226 is thicker, stiffer and has a more waxy tactile sensation.

Figure 14. Spectra Shield ® II SA-4144 panel by Honeywell. The sample is delaminated/stratified, showing two separate panels with two layers of yarns in each of them, positioned perpendicularly; source: author's own photo archives.

4. Contemporary personal ballistic protection (PBP)

Ballistic protection, especially soft ballistic protection armour, has undergone a significant material and design revolution in recent years. Armour panels, meaning the essential elements providing protection in ballistic vests, consist of a ballistic panel, which is usually a set of woven or non-woven structures. They are protected by a cover from environmental influences. Of course, neither the cover for the panel nor the carrier—another element of the ballistic vest—is intended to provide ballistic protection. The carrier refers to the textile elements, usually made of nylon, which are visible from the outside when the person is wearing the ballistic vest. The principal purpose of the carrier is to support and secure the panels to the wearer's body. This subchapter predominantly discusses so-called soft body armour and hard body armour—both of these types of protection are mentioned in the classification presented below. However, the functions, designs and the materials utilized in these two groups are different.

4.1. Soft body armour

Soft body armour consists of flexible panels of ballistic materials. This type of armour is designed to protect from assaults with pistols and revolvers—generally, handguns. Due to its lower weight when compared with hard body armour, it is rather intended to be utilized for extended daily wear, for several hours, e.g. armour worn by law enforcement officers, correctional officers and guards. If it is worn under a uniform, it is called concealable armour. The soft armour panels are typically constructed of multiple layers of ballistic-resistant materials, e.g. Kevlar fabrics, Spectra or Dyneema UD non-woven materials as presented in **Figures 6–14**. The number of layers in the panel influences the panel's overall performance, which means the ability to resist the energy of projectiles. Normally, each layer is supposed to absorb and dispatch a certain amount of energy, which is less and less when transferred to the next layer closer to the body. When a projectile strikes the panel, the yarns and the fibres catch the bullet due to the mutual interlacing of the yarns (in a woven structure) or superimposing yarns from different layers of the panel (unidirectional panels). These fibres have the ability to absorb and dissipate (disperse) the energy of impact, which is passed on from the bullet to the panel and to be specific to each of the panel's layers gradually. This process causes the bullet to deform or 'mushroom'. This ability of the panel to absorb and disperse the energy of the bullet is the key to its ability to reduce blunt force injury to the body resulting from bullets that do not perforate the panels. As the fibres in a panel jam a bullet, the energy of the bullet pushes the panel into the body of the wearer, potentially resulting in injury to the torso. The cone made in layers of a panel is schematically presented in **Figure 15**. This type of non-penetrating injury can cause severe contusions (bruises) and can cause damage to the internal structures of the body (musculature, bones, ligaments, organs and vascular system) that may even result in death [43, 46].

4.2. Hard body armour

Hard armour, on the other hand, consists of rigid panels or plates. Hard armour is designed to offer greater protection against higher threats than soft armour could bear on its own. Hard
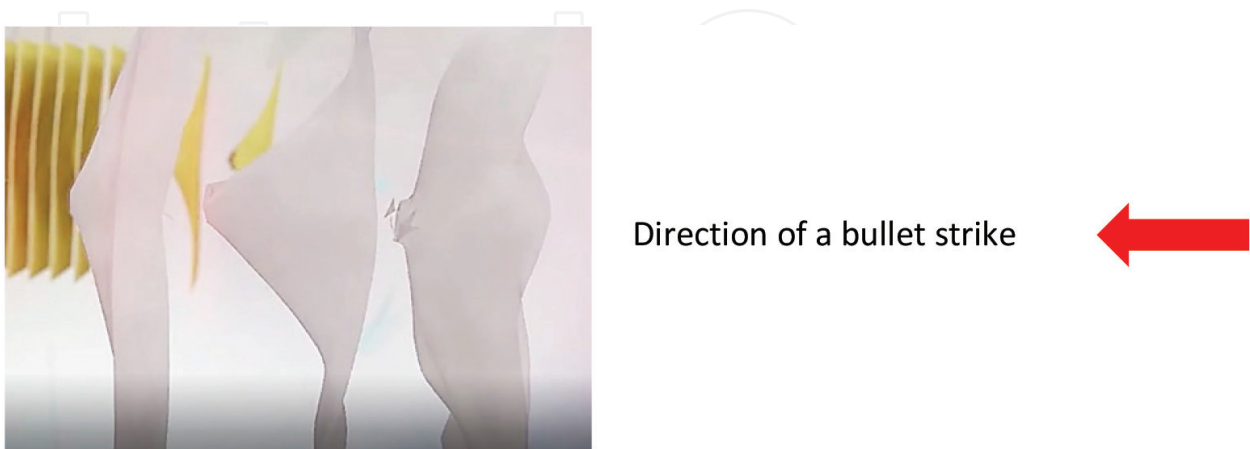

Direction of a bullet strike

Figure 15. Characteristic cone shapes in the layers of a soft protective panel elements after the bullet struck and perforated them, heading in the direction of the next layer. The cones become smaller due to the smaller amount of bullet kinetic energy transferred to each consecutive layer; prepared on the basis of a Tensylon™ commercial released by DuPont.

armour plates are used in tactical armour. Tactical armour is typically a combination of a hard armour plate and soft armour panels, making it thicker and heavier than soft armour alone. The side of the panel that faces away from the body is referred to as the strike face, because it is the side that is intended to be hit by the bullet. The other side of the panel that is worn against the body is referred to as the wear face or body side.

Hard armour plates may be constructed from ceramics, compressed laminate sheets, metallic plates or composites that incorporate more than one material, e.g. CeraShield™ and Cercom® by Coorstek or Tensylon [43, 48–50] as presented in **Figure 16**. Tensylon™ is currently being used in-theatre as a spall liner in mine-resistant ambush protected (MRAP) vehicles, e.g. Tensylon™ HSBD 30A is a bi-directional laminate. The hard armour plates act in one of the following ways: they can capture and deform the bullet or they can break up the bullet. In both instances, the armour then absorbs and distributes the force of the impact. Although some hard armour plates are designed to be used by themselves in a carrier, in the majority of cases, they are designed to be used in-conjunction (IC) with a soft armour panel. Many hard armour plates are designed to be used with a specific soft armour panel to achieve a desired level of ballistic protection. They are introduced into the ballistic set by adding pockets to the front and rear of a soft armour's carrier. The hard armour plates are inserted into these pockets over a portion of the underlying soft armour panel. The hard armour plate component of the IC armour is clearly marked to identify the corresponding model of soft armour panel with which it is to be utilized. The most commonly used ceramics that can be used as stand-alone monolithic plates for armour purposes are aluminium oxide (Al_2O_3), silicon carbide (SiC) and boron carbide (B_4C). Al_2O_3 is usually the most economical alternative, but the final protection solutions using Al_2O_3 are heavier, since Al_2O_3 has the highest density and the lowest ballistic efficiency of the three ceramic types [49, 51]. B_4C is the hardest ceramic; but at high-impact pressures, an amorphization process weakens the ceramic. This is problematic when the threat is an armour-piercing projectile at high velocity. Ceramics with a small grain size usually perform better than ceramics with larger grain sizes.
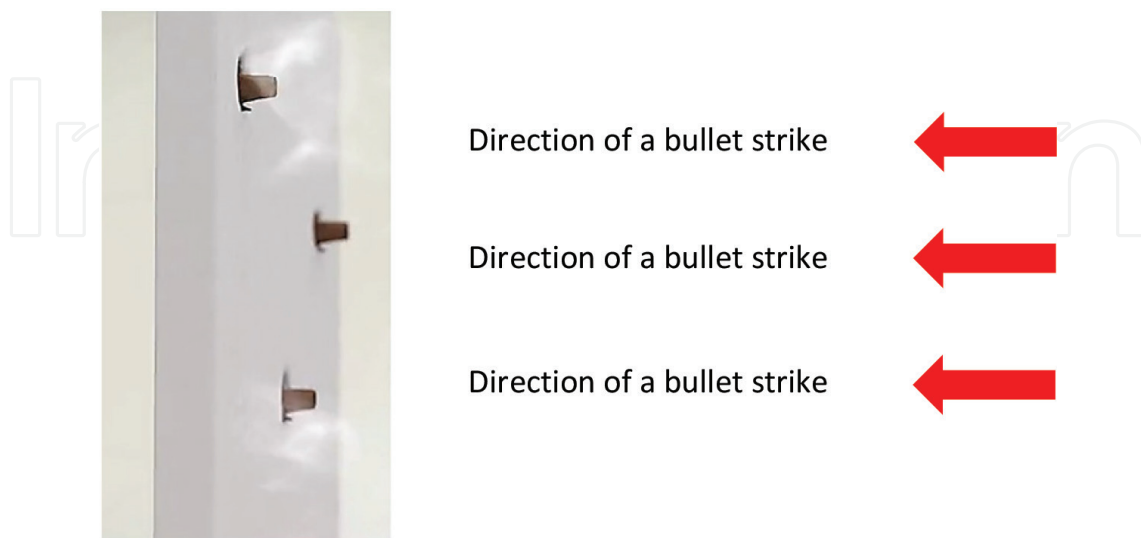

Direction of a bullet strike

Direction of a bullet strike

Direction of a bullet strike

Figure 16. The characteristic indentions in the hard body armour and mushroomed projectiles after they struck the panel and perforated it; prepared on the basis of a Tensylon™ commercial released by DuPont.

4.3. Combination armours

Combination armours are specially designed to provide protection against both firearms and edged or stabbing weapons. It means that in these armours, the protective panels are composed of layers of materials that are stab resistant as well as layers of materials that are ballistic resistant. These types of armours are also called *dual threat* or multiple threat armours. The National Institute of Justice (NIJ) in the United States provides a list of those combination armours that have been tested and found to be compliant with both NIJ Standard-0101.06 and NIJ Standard-0115.00 for both ballistic and stab resistance [52]. There is an example of a multi-threat protection by DSM shown in **Figure 17**.

4.4. Anti-blunt trauma plates

These plates are made of layers of ballistic-resistant fabrics, metals, laminate sheets or other materials. They are referred to as trauma packs or plates because they are intended to minimize blunt force trauma injury to the torso resulting from a bullet striking an armour. Sometimes these plates are inserted into the vest carriers to provide some additional ballistic protection, although this is not their prime purpose. They can be easily distinguished from traditional hard armour plates due to their size, typically anti-blunt trauma plates smaller and thinner. These anti-blunt trauma plates are usually placed in the centre of the chest in pockets in front of (or, less commonly, behind) the front soft armour panel. As is the case of armour panels, the orientation of trauma plates and packs matters. They are marked using the same convention as is used for armour panels. Some armours incorporate multiple trauma packs.

4.5. In-conjunction armour (IC)

Usually, hard body armour plates are meant to be used with a specific type of soft body armour panel to accomplish a specific and required level of ballistic protection. In such case, these hard body armours are not designed to be used alone. These hard body armour plates are inserted into the pockets in the front and at the back of the soft body armour carrier.

Figure 17. Dyneema® Multi-threat level protection with pictograms describing its properties by DSM; source: http://www.dsm.com/products/dyneema/en_GB/applications/personal-armor/ballistic-anti-stab-vests.html [53].

5. Contemporary classification of PBP

The classification of the materials for impact protection is quite complex due to many existing materials and existing protection elements. In **Figure 18**, a simplified graphical version of this classification is presented. It takes into consideration three major approaches: textile personal protection versus non-textile personal protection, ballistic personal protection versus non-ballistic personal protection and hard body armour versus soft body armour.
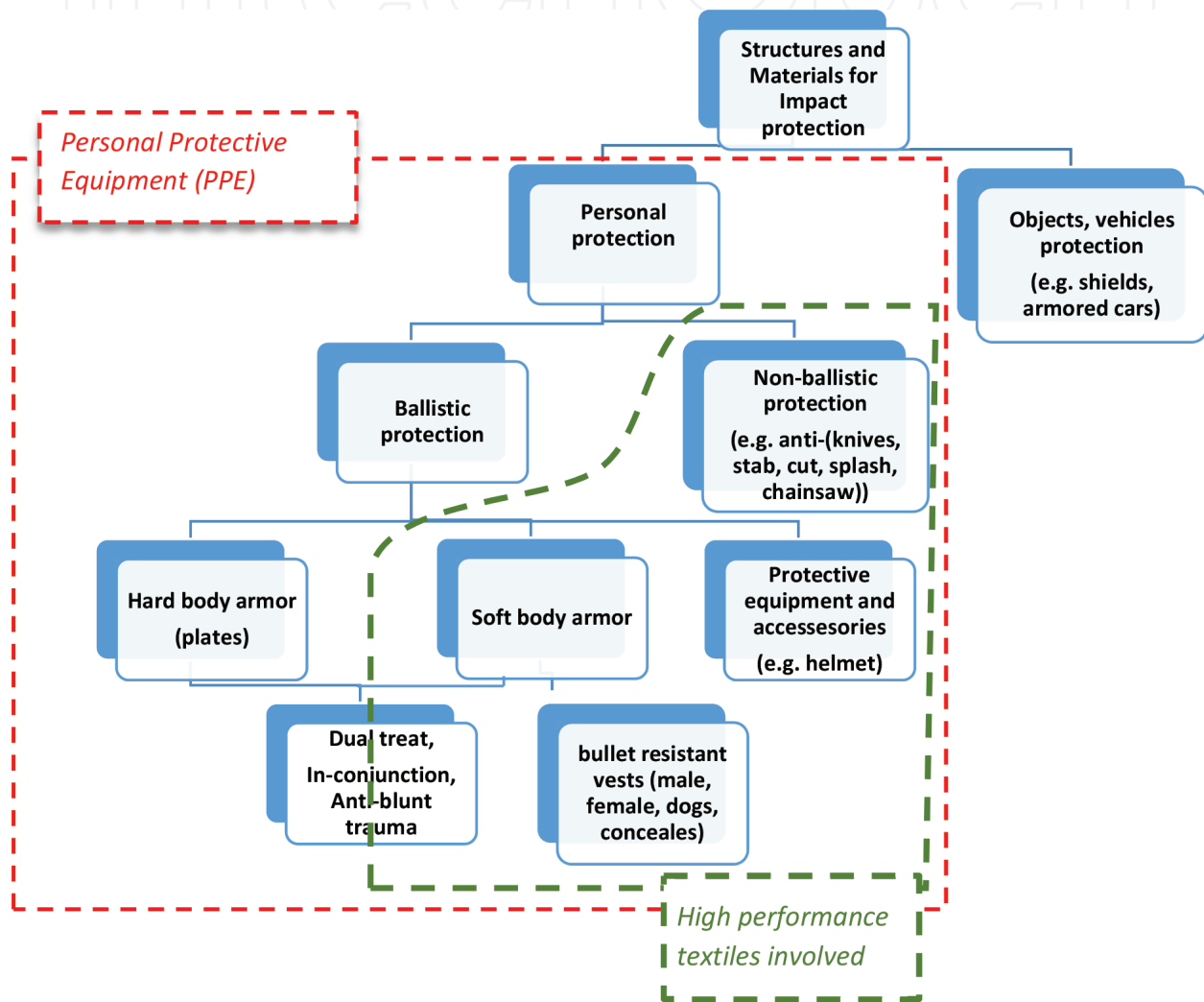
Figure 18. Contemporary classification of PBP elements.

6. Helmets as elements of personal protection

Similar to protective vests or other elements of body armour, helmets underwent significant changes and developments in terms of their design and applied materials. Helmets began as head protection made from woven fabric with some elements of leather and ceramics. Later

on, helmets were made from metal and had three main functions—protection, deterrence and decoration. Today, the contemporary advanced combat helmet (ACH) has only one main function—protection. One of the key advances, which has influenced ballistic helmets, was the development of aramid fibres in the 1960s, which led to Kevlar®-based helmets. The Department of Defense (DoD) in the United States and other relevant national and international institutions have continued to invest in research to improve helmet performance, through better design and materials, as well as better manufacturing processes. **Tables 2–6** and **Figures 19–23** present an overview of contemporary ballistic helmets, which are available on the market.

6.1. History of head protection

A variety of threats lead to head injuries in the battlefield. Since World War II, the predominant threats have been from fragmentation and ballistic threats from explosions, artillery and small arms fire; blunt trauma caused by translation from blast, falls, vehicle crashes and impact with vehicle interiors and from parachute drops and exposure to primary blasts. Injuries, usually involving division of tissue or rupture of body tissue coming from an explosive source (e.g. fragmentation from bombs, mines and artillery), dominate all injuries, including bullets. Non-battle causes, including blunt traumatic injuries, produced nearly 50% of the hospitalizations for traumatic brain injury in Iraq/Afghanistan. There is no biomechanical link in the current test methodology between the back face deformation (BFD) assessment and head injuries from behind-helmet deformation. Different variations of steel helmets were used by forces in the United Kingdom and the British Commonwealth during World War I and later. Since 1945, the escalation in the lethality of ballistic threats, resulting in higher fatalities and injuries, is observed. The bullets and shrapnel in World War II had greater mass and higher velocities. As was the case in World War I, soldiers initially resisted wearing helmets. They felt that the 3.5 lb helmet was too heavy and that it limited the hearing, vision and mobility of the wearer. However, the troops quickly accepted the trade-off when they observed the lethality of the munitions on the battlefield and recognized the protection provided by the helmet. The personnel armor system for ground troops (PASGT) was the first helmet to utilize Kevlar. The name and the abbreviation PASGT refer to both vests and helmets made of Kevlar and they were used by all military services from the mid-1980s to around the middle of the last decade. These helmets are still being used by some services but will be replaced in the future [21].

Timeline	Year 1980
Helmet types	Personnel armour system for ground troops (PASGT)
Material composition	Aramid fibre (Kevlar®)
Protection level	Originally, only Level II and contemporarily produced PASGT helmets met Level IIIA ballistic penetration protection according to the contemporary standard of NIJ 0106.01 as presented in product information folders of producers of these helmets
Technical parameters	Presently provide a full-coverage-style helmet, four-point adjustable retention system
Provider(s)/Price	3M company; https://www.3m.com/~625 USD

Table 2. An overview of personnel armour system for ground troops (PASGT) helmet.

Timeline	Year 2001—MICH & Year 2003—ACH
Helmet types	Modular integrated communications helmet (MICH) Advanced combat helmet (ACH)
Material composition	MICH is a composite helmet made of Kevlar intended for use by special forces. ACH was elaborated on the basis of MICH. ACH uses ballistic fibre such as Kevlar or Twaron
Protection level	MICH: Level IIIa High Cut MICH Helmet
Technical parameters	Mass of MICH without accessories is about 1.36 kg
Provider(s)/Price:	MICH/cost starts at 449.99 USD; source: http://infidelbodyarmor.com/helmets-c-10/

Table 3. An overview of modular integrated communications helmet (MICH) and advanced combat helmet (ACH).

The US Special Operations Command designed and developed the modular integrated communications helmet (MICH) as a replacement for PASGT (**Figure 19**). MICH incorporated several changes, including improved Kevlar aramid-fibre reinforcement, leading to better protection. These helmets also allowed better fit and integration of communication headsets. MICH was adopted by the US Army in 2001–2002 as its basic helmet and renamed the advanced combat helmet. The Marine Corps decided to use a design profile that was similar to the PASGT and called it the light weight helmet (LWH). There were also developments in helmet retention systems. The MICH, ACH [54] and LWH helmets switched to a multi-pad and four-point retention system (**Figure 20**) that had better impact protection while providing increased comfort. The next major advance in helmet technology resulted from a combination of advances in materials and manufacturing processes. As soon as UHMWPE was developed and later on adopted by key players producing ballistic shields, the producers of ballistic helmets adopted it as well.

The future assault shell technology (FAST) helmet is significant for its early use of UHMWPE material and its novel design (**Figure 21**). The next solution, enhanced combat helmet (ECH), delivers much better protection against fragments compared with ACH, due to a shift to uni-directional UHMWPE fibre in a thermoplastic matrix. The shift was also enabled by a new generation of preforms and manufacturing methods appropriate for UHMWPE.

Timeline	2010
Helmets types	FAST
Material composition	Ballistic shell made of a hybrid composite of carbon, unidirectional polyethylene and woven aramid
Protection level	Level IIIa
Technical parameters	Thickness of the shell: 6.43 mm
Provider(s)/Price	Ops-Core: 1,662 USD; source: http://www.ops-core.com/ fast-mt-super-high-cut-helmet/

Table 4. An overview of future assault shell technology (FAST) helmet.

Timeline	2012/2013
Helmet types	ECH
Material composition	Dyneema HB80 UD composite
Protection level	Level IIIa
Technical parameters	Head protection when parachuting for military paratroopers, head protection from bumping objects for military ground forces and head protection against handgun rounds and ballistic fragments. The ECH's profile is very similar to the ACH but is thicker. The helmet's shell is made of an ultra-high-molecular-weight polyethylene material. It protects 35% better against small-arms fire and fragmentation than the ACH.
Provider(s)/Price	3M company in collaboration with Ceradyne; 3M™ Defense Protection Systems/starts from 500 USD

Table 5. An overview of enhanced combat helmet (ECH) helmet.

The US government launched the helmet electronics and display system-upgradeable protection (HEADS-UP) programme in 2009. It leverages multiple efforts—in the areas of ballistic materials (transparent and non-transparent), high-resolution miniature displays and sensors—to design a modular-integrated headgear system that takes into account the relevant ergonomic considerations. HEADS-UP has focused on developing a technical data package of design options and trade-offs to build a modular, integrated headgear system.

The major threats that have caused head injuries in recent conflicts can be classified into three groups: ballistic, blunt and blast. Fragmenting weapons, including artillery, mines, mortars and other sources of explosions, are the principal source of wounding on the modern battlefield. These weapons, including improvised explosive devices (IEDs), have a multitude of fills/wounding mechanisms.

There is limited information on the effect of primary blast on the head. Traumatic brain injury (TBI) associated with blast exposure in operation enduring freedom (OEF)/operation Iraqi freedom (OIF) is estimated at up to 20% of deployed service personnel. The current helmet is not designed with considerations for primary blast, but there is substantial experimental evidence that the ACH helmet is protective against primary blast for most direct exposures.

Timeline	2013/2014
Helmet types	HEADS-UP
Material composition	UHMWPE
Protection level	Level IIIa
Technical parameters	Improved ballistic materials, non-ballistic impact linear materials and designs, transparent as well as heads-up display technologies, and better eye, face and hearing protection. The helmet displays integrated electronics in the helmet, a HEADS-UP display powered by an android phone, and a pneumatic linear system that meets the 14 feet/second impact requirement to reduce traumatic brain injuries.
Provider(s)/Price	Gentex Corporation/price unknown

Table 6. An overview of helmet electronics and display system-upgradeable protection (HEADS-UP) helmet.
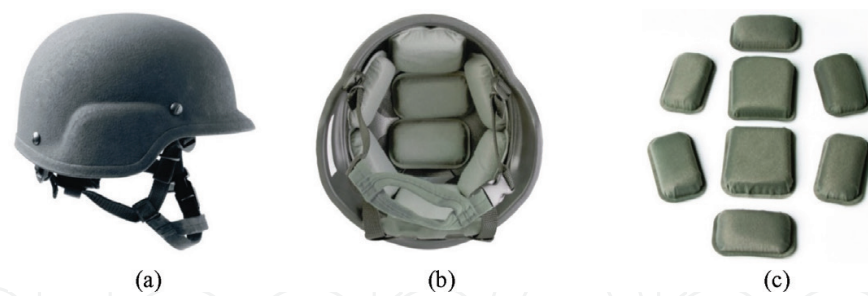
Figure 19. PASGT ballistic helmet; (a) side view on skull; (b) interior of the helmet; (c) pads of the helmet; source: CopQuest, Inc.; images available at https://www.copquest.com/protech-pasgt-tactical-helmet_89-1015.htm.
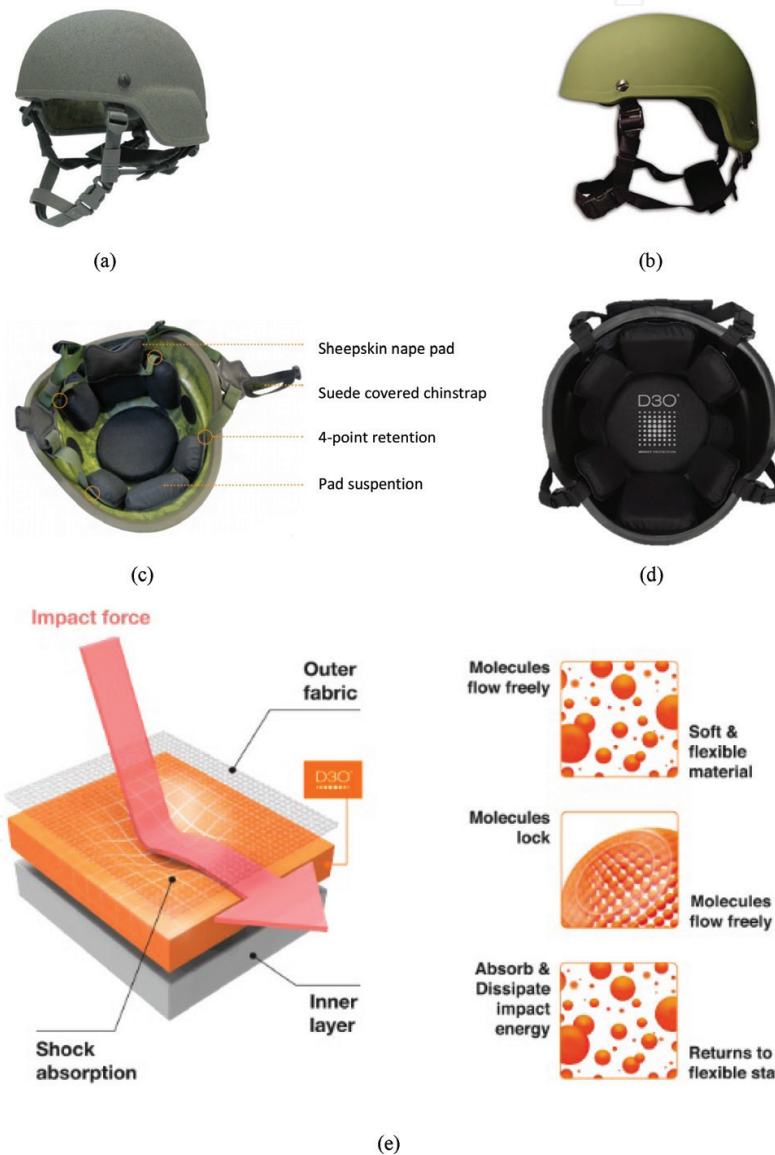

Figure 20. MICH and ACH ballistic helmets. (a) Side view of a MICH helmet; source: http://infidelbodyarmor.com/helmets-c-10/. (b) Side view of an ACH helmet; source: http://www.gentexcorp.com. (c) Interior of an ACH helmet; source: http://www.gentexcorp.com. (d) The 3M™ Ultra-Light Weight (ULW) Ballistic and Bump Helmet is manufactured by Ceradyne, Inc., a 3M™ Company source: https://www.d3o.com/defence/3m/. (e) Schematic presentation of impact protecting materials utilized in the pads of the helmets—e.g., (d). D3O technologies are based on non-Newtonian principles—in its raw form, the material's molecules flow freely, allowing it to be soft and flexible, but on impact, lock together to dissipate impact energy and reduce transmitted force; source: https://www.d3o.com/.
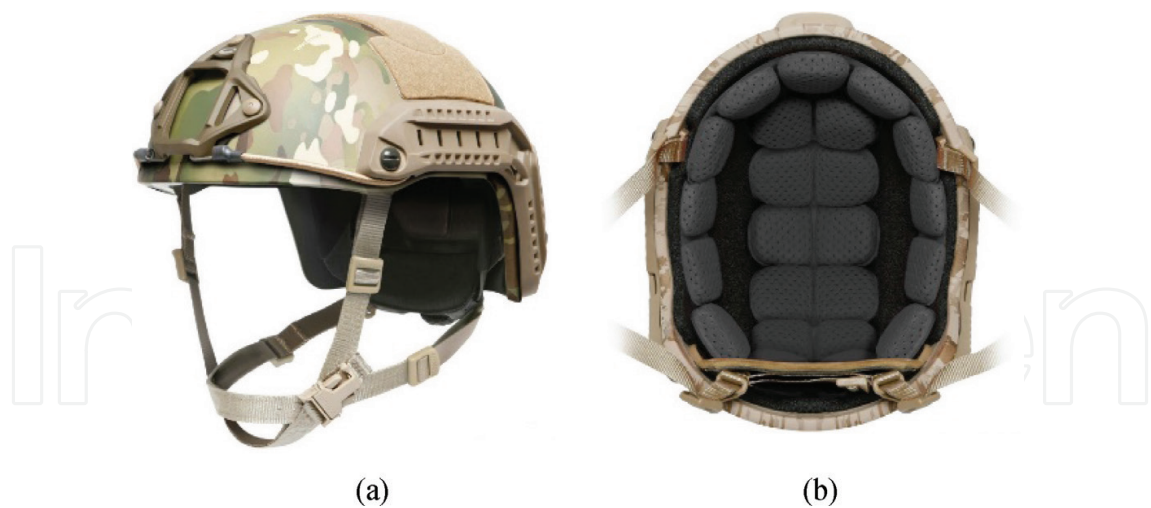
(a)   (b)

Figure 21. (a) A side view of a FAST Maritime (MT) Super High Cut Helmet. Ear cut geometry is 16 mm higher than the FAST Ballistic High Cut (XP) shell shape, allowing for clearance of larger headset style communications devices. (b) An interior of the helmet; source: http://www.ops-core.com/system-platforms/ballistic-helmets/fast.

6.2. Primary blast

For severe TBI from blast exposure, there may be clear neurological changes, including reduced levels of mentation, unconsciousness and other dysfunctions. For milder exposures, possible consequences include neurological deficits, depression, anxiety, memory difficulty and impaired concentration. Epidemiological data, experimental results and computational models suggest that the ACH helmet does not exacerbate blast exposure. Modern ballistic wounding is generally differentiated between rifle and handgun rounds by velocity. For example, high-velocity tumbling rounds such as typical 5.56 mm projectiles (800 m/s or above muzzle velocity) have qualitatively different wounding behaviour than .22 calibre handgun ammunition (~330 m/s muzzle velocity), although they have similar diameters [21].

Figure 22. A side view of enhanced combat helmet (ECH); source: https://en.wikipedia.org/wiki/Enhanced_Combat_Helmet.

Figure 23. (a) HEADS-UP worn by soldiers; (b) a side view of HEADS-UP; (c) schematic presentation of streams of air inhalation and exhalation in the HEADS-UP; source: http://www.gentexcorp.com/assets/base/Brochures/GroundCatalog. pdf.

7. Testing methodology for PBP

7.1. Panels

The most recognizable is the work performed by NIJ in the United States, which elaborated and has improved the methodologies for testing different sorts of protections against ballistic and non-ballistic threats. This standard entitled Ballistic Resistance of Body Armour, NIJ Standard-0101.06 also classifies different personal body armours into six types (IIA, II, IIIA, III, IV + a special type) by level of ballistic performance, which are presented in **Table 7**. A special test class is defined to allow armour to be validated against threats that may not be covered by the first five standard classes presented in **Table 7**. A typical range configuration (a place where the ballistic tests take place) is presented in **Figure 24**. If the test is to be performed using a handgun rounds, the armour panel should be fixed at the distance 5.0 ± 1.0 m from the muzzle of the test barrel, and for rifle rounds, the armour panel should be fixed 15 ± 1.0 m from the muzzle of the test barrel. In order to minimize the possibility of excessive yaw at impact, or for other range configuration reasons, the distance may be adjusted for each threat. However, the distance should not be less than 4 m for any tested rounds [55].

NIJ Standard-0101.06*

Protection level	Ammunition type	Projectile mass	Projectile velocity
IIA	9 mm FMJ RN	8.0 g ≅ 124 gr	373 m/s ± 9.1 m/s
	0.40 S&W FMJ	11.7 g ≅ 180 gr	352 m/s ± 9.1 m/s
II	9 mm FMJ	8.0 g ≅ 124 gr	398 m/s ± 9.1 m/s
	357 Magnum JSP	10.2 g ≅ 158 gr	436 m/s ± 9.1 m/s
IIIA	0.357 SIG FMJ FN	8.1 g ≅ 125 gr	448 m/s ± 9.1 m/s
	0.44 Magnum SJHP	15.6 g ≅ 240 gr	436 m/s ± 9.1 m/s
III	7.62 mm FMJ	9.6 g ≅ 147 gr	847 m/s ± 9.1 m/s
IV	0.30 AP	10.8 g ≅ 166 gr	878 m/s ± 9.1 m/s

A special type defined by the Standard-0101.06 separately

*The data concern only new and unworn armour, although the standards foresee also the tests on conditioned armour. In such case, the allowed parameters, namely the velocities of the projectiles are lower.

FMJ RN–Full Metal Jacketed Round Nose; JSP–Jacketed Soft Point; SIG–Schweizerische Industrie Gesellschaft–Swiss Industrial Company, a producer of the type of the gun; FN–Flat Nose; SJHP–Semi Jacketed Hollow Point; AP–Armor Piercing.

Table 7. An overview of the personal body armour levels of protection according to the NIJ Standard-0101.06 [55].

Calibre of the gun is the approximate internal diameter of the barrel, or the diameter of the pro-jectile it fires, e.g. 40 calibre of a firearm refers to the barrel diameter of 0.40 of an inch. The metric system is also popular to describe the diameter of a bullet or a barrel. In such case, the diameter is given in millimetres, e.g. 9 mm.
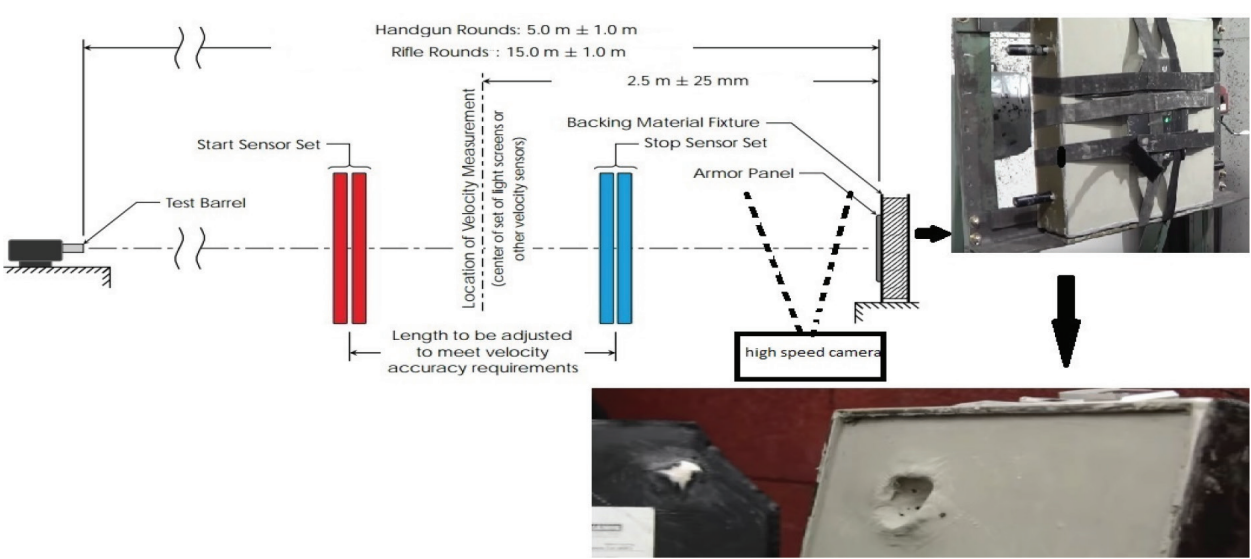

Figure 24. A graphical presentation of a set up for testing the armour panels at the laboratory testing range and images presenting backface deformation (backface signature depth) of a backing material and its response to ballistic impact on the plasticine (or clay) informing about the potential trance in a human body (blunt trauma) that that the fired projectile may cause. Although in an original graphical presentation of a set up presented in the Standard-0101.06 of NIJ, there is no high-speed camera, in many cases, this type of the camera is placed to observe and record the collision of projectiles with a protective panels; source: adapted from graphic [53]; images: top—Oregon Ballistic Laboratory test; bottom—modified on the base of IIIA Soft Body Armor Penetration in Ballistics Clay—AR500 Armor®.

Grain [gr] is a unit of mass. 1 g is approximately 15.43236 grains.

Other present or past standards being partially equivalents of NIJ Standard-0101.06 are:

- MIL-STD-662F, Military Standard: V50 Ballistic Test for Armor [56]

The purpose of this standard is to provide some general guidelines for procedures, equipment, physical conditions and terminology for determining the ballistic resistance of metallic, non-metallic and composite armour against small calibre arms projectiles. The ballistic test procedure described in this standard determines the V50 ballistic limit of armour. This test method standard is intended for usage in ballistic acceptance testing of armour and for the research and development of newly created armour materials.

- *UK Standard—UK/SC/5449*; Ballistic Test Method for Personal Armours and Lightweight Materials [57].

- *NATO Standard—*STANAG 2920 [58].

Ballistic test method for personal armour materials and combat clothing—STANAG 2920 is used to measure materials ability to stop fragments and shrapnel. The measuring technique was originally developed for body armour but now see general use in all situations where fragments are the primary concern. For instance, STANAG 2920 is used to measure Add-on-Armour systems for armoured vehicles.

Tests according to STANAG 2920 are conducted by shooting Fragment Simulating Projectiles (FSPs) onto the test specimen with different velocities while measuring the velocity of each FSP. By altering the velocities, after a number of shots, an estimate of the ballistic limit can be obtained, which is the speed up to which the material defeats the fragment.

7.2. Helmets

Based on the US testing protocols, one may say that the test protocol involves several shots with a specific calibre gun at the specific speed and the specific location on the helmet to prove the resistance (total or not) of the helmet. Overall, tests are aiming at assessment of three parameters, namely resistance to penetrate (RTP), the backface deformation (BFD) and probability V50, that the helmet is equally likely to stop or not stop an object striking at a specific velocity. The original army first article testing (FAT) procedure protocol consisted of 20.9 mm shots (four helmets and shots at five specified locations on a helmet). A manufacturer's helmet design was deemed to pass FAT for penetration if there were zero penetrations out of the 20 shots. In 2012, with Director of Operational Test and Evaluation's (DOT&E's) approved a new two-stage protocol. It involves performing a 0-out-of-22 test in the first part, and if the helmet design passes the first part of the test, then a second 17-out-of-218 plan is executed, for a total of 240 shots and a combined acceptable number of penetrations of 17 [21].

The helmets are tested in the laboratories having a very similar set up for testing as in case of testing the protective panels, which is presented in **Figure 24**. However, instead of the panel, one utilizes a model of the head with a helmet on it.

For combat helmets, the current testing methods and measures have no connection to research on head and brain injury. The lack of connection between injury and current test methods and

measures is a significant concern. During such test, the helmet, needs to be tested, is fastened to a headform packed with modelling clay, and a rifle-like device is used to fire various projectiles into the helmet. The clay is used as a recording medium for: (1) assessing penetration should the projectile or portions thereof pass through the helmet into the clay as presented in **Figure 25** and (2) measuring the deformation of the helmet, where a trace is left in the clay surface as a result of the ballistic impact pushing the helmet into the clay.

One of the critical issues with the clay (Roma Plastilina #1) is that the clay is time and temperature sensitive in that, its properties can change significantly over a 45-minute period as it cools. These effects are likely to affect BFD measurements [21].

7.3. Resistance to penetration (RTP)

RTP is measured by shooting a given ballistic projectile at a set of helmets and counting the number of complete penetrations. Most ballistic impacts penetrate the helmet to some degree, so the DOT&E FAT distinguish between complete and partial penetrations. A complete penetration in RTP testing is defined as: *Complete perforation* of the shell by the projectile or fragment of the projectile as evidenced by the presence of that projectile, projectile fragment or spall in the clay, or by a hole which passes through the shell. A partial penetration is defined as 'any fair impact that is not a complete penetration'. The intuitive notion is that a projectile that penetrates the shell is able to cause more serious head injuries than a projectile that does not, but there is no other linkage between what is measured and head injury [21].

7.4. Backface deformation (BFD)

After mounting the headform in the test fixture and mounting the helmet on the headform, the helmet is removed from the headform, and the clay surface is scanned with, for instance, a Faro® Quantum Laser Scan Arm laser or in other way. The helmet is then reattached to

Figure 25. A ballistic test set up for testing a MICH ballistic helmet against 9 mm calibre; source: www.kick-az.com.

the headform, and the shot taken. The helmet is again removed from the headform and inspected for penetration and perforation. The clay is rescanned with the FARO laser to calculate BFD or the clay indention is measured other way. It is unclear how well BFD from ballistic impact characterizes the effect of blunt force trauma, which is one of the main types of brain injury that the helmet is intended to protect against. The choice of the helmet BFD threshold values—25.4 mm for front and back shots and 16 mm for side and crown shots does not have a scientific basis [21].

7.5. V50 test

It refers to estimating the bullet speed at which there is a 50% chance of penetration. This test uses a witness plate mounted inside the headform rather than packing the headform with clay as is done with RTP/BFD testing. Because of this difference, the DOT&E FAT protocol defines a V50 complete penetration as a shot where impacting projectile or any fragment perforates the witness plate resulting in a crack or hole, which permits light passage. A break in the witness plate by the helmet deformation is not scored as a complete penetration. The definition of what constitutes a penetration, and how such penetrations are measured, differs between RTP and V50 tests. V50 specifies a 'hole which permits light passage' whereas RTP does not [21].

8. Stab resistance of personal body armour (PBA)

This type of protection is applied to reduce the risk of stabbing by knives or spikes, etc. especially in places like correctional facilities. There is a standard entitled stab resistance of personal body armour by NIJ, 0115.00 [52], which establishes minimum performance requirements and methods of test for the stab resistance of personal body armour intended to protect the torso against slash and stab threats. The threat posed by a knife depends, among other things, on its sharpness, pointedness, style, handle and blade design, attacking angle, the physical condition of the attacker and the skill of the attacker. Because these parameters can vary widely from one situation to the other, armours that will defeat a standard test blade may not defeat other knife designs under similar conditions or the same knife design if other attacking parameters are changed [52]. The threats analysed in this standard came from hand-delivered impacts with sharp-edged and/or pointed instruments which points or tips lie near the centreline of the clenched fist holding the weapon. PBAs covered by this standard are classified into one of two distinct protection classes depending on the type of threat. Within each threat protection class, the armour is further classified into one of three protection levels. The levels of protection indicate the stab energy the vest is expected to bear. The first protection class is intended to deal with threats that might be expected on 'the street' from high quality, commercially machined edged knife blades. This class is referred to as the 'Edged Blade' class. The second protection class is intended to deal with threats that might be expected in correctional facilities and these are weapon types constructed by inmates. These are lower quality knife blades and spike style improvised from other materials. This class is referred to as the

'Spike' class. The three levels of protection presented in this standard were derived from the frequency distribution of the energy that can be delivered by a male population using several stabbing techniques. The lowest energy level corresponds to the 85th percentile (corresponds to the E1, level 1), the next energy level corresponds to the 90th percentile (E1, level 2) and the highest energy level corresponds to the 96th percentile (E1, level 3). For any given protection level, the test protocol requires the knife blade or spike to impact the armour test sample at two distinct energy levels. At the given condition, a maximum blade or spike penetration of 7 mm is allowed. The penetration limit was determined through research indicating that internal injuries to organs would be extremely unlikely at 7 mm of penetration. The test protocol then requires an overtest condition where the knife blade or spike kinetic energy is increased by 50% (e.g. 24 + 50% × 24 = 36, E2, level 1). At this higher energy condition, called 'E2', a maximum blade or spike penetration of 20 mm is allowed. This overtest is required to ensure that there is an adequate margin of safety in the armour design [52] (**Table 8**).

During stab-resistant drop tests, the front and back panels of two complete body armours are tested for resistance to stab penetration using a different testing set up than the one for ballistic tests. The exemplary test set up is presented in **Figure 26**. The stabbing element is dropped on the fixed protective panel to observe and measure whether there is a perforation.

Apart from an angle indent into the panel, the tests take into consideration the stab energy level and the weapon type itself.

Protection level	'E1' Strike Energy [J]	'E2' Overtest Strike Energy [J]
1	24 ± 0.50	36 ± 0.60
2	33 ± 0.60	50 ± 0.70
3	43 ± 0.60	65 ± 0.80

Table 8. Stab-resistant protection level strike energies [52].
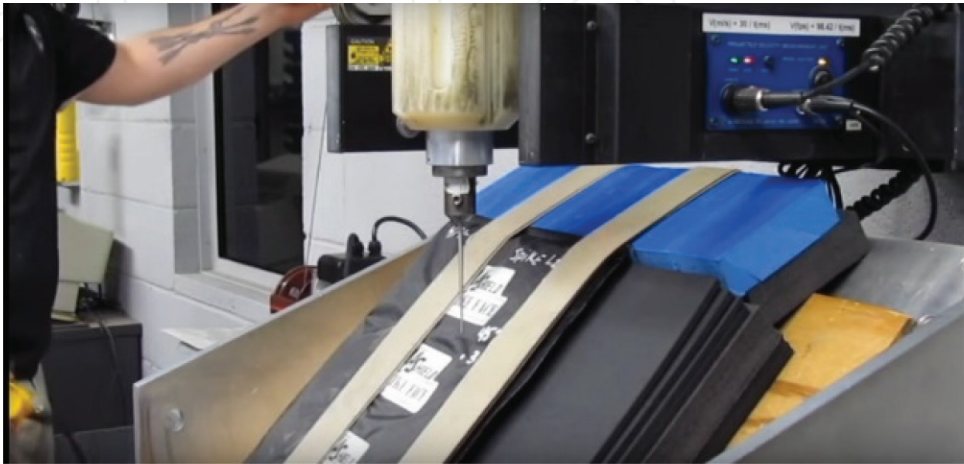
Figure 26. Stab-Resistant Panel NIJ 0115.00 Level II Spikes Test; source: http://www.aashield.com/.

9. Other protective elements

9.1. Female armour

The bust area of a female body armour is shaped by a unique process, which eliminates cutting or cut depending on the producer of the front ballistic panel. It enhances wear comfort and mobility without sacrificing ballistic performance. The example of a female ballistic personal protection is in **Figure 27**.

9.2. Improvised explosive devices (IED) and sappers

The risks that many active soldiers present at the current world scenes may face are very often related to IED, which are homemade bombs unique in their construction, size and potential lethal effect. Therefore, IED remains in the contrast with commercially available weapons, which is controlled. Since IED is unique, it is impossible to be fully prepared and protected against its effects. Persons located in the explosion radius get affected by the penetration of the elements being hidden in the IED when it is constructed, e.g. spikes, nails, etc. or in other way because they are in the blast region of IED. Blast is defined as a detonation of liquid or solid explosive material results in the generation of gaseous products in the pressure range of 150,000 atmospheres or 1.5 billion Pascals (1.5 GPa) and temperature of 3000 Kelvin. In many cases, if there is any suspicion about the bomb and there is a time to make an attempt to disarm it, a person called sapper may be sent to the scene. Clearing the scene is only one of the duties of a sapper, among demolitions, bridge-building, field defences as well as building, and reparations. Sappers are called pioneers, combat engineers or field engineers. The personal protection for

Figure 27. (a) Female ballistic-resistant vest called Enforcer XLT; source: http://www.usarmor.com/products/concealable/enforcer-xlt.

sappers called explosive ordnance disposal (EOD) suit or a blast suit is far more complexed that in case of law enforcement, correctional officers or regular soldiers as it needs to cover the whole body of the sapper. In order to enhance the protection, some of the parts of the bomb suit overlap. An example of the EOD personal protective equipment can be Med-Eng EOD 9 or Med-Eng EOD 10, mass about 33.4 kg. These are new generation bomb suits and helmets composed of jacket, an integrated groin protector, trousers and boot covers for integrated blast protection against IEDs and bombs. In order to improve the protection, some studies on specific elements of the bomb suits are performed, e.g. development of pelvic textile protection for soldiers [59].

9.3. Concealable body armour

The idea, which stands behind producing this type of protection, is to hide the fact of wearing it on the body. Therefore, the carrier of the ballistic panel is having a form of a suit vest. It is meant for politicians and business people. Usually, the available level of protection in case of the concealable body armour is IIIa according to NIJ.

9.4. Protection for police dogs

A police dog, often called K9 (**Figure 28**), is a specially trained type of dog to assist law enforcements and also military service in searching for drugs and explosives, searching for lost people, looking for crime scene evidence and protecting police officers who handle them. These dogs are equipped in protective vests, which are usually dual threat protections, it means that they protect dogs from firearms and stabbing. These vests are cut from the same

Figure 28. Detroit police K9 dog wearing bullet-resistant vest, 9 August 2016; source: Robin Buckson/Detroit News available at http://ktar.com/story/1220231/detroit-police-dogs-to-sport-bullet-resistant-vests/.

Kevlar® bullet-resistant cloth as their human partners, covering all the vital organs. The vests are designed so that the dogs can wear without reducing their mobility and efficiency. The dogs' protective vests, like protective ballistic vests for humans, undergo field tests.

9.5. Three-dimensional (3D) structures for ballistics

One of the interesting and significant innovations in soft body armour is a completely different structure of the protective fabric from these, which were presented in this chapter so far, namely 3D structures for ballistics. The idea of this invention is to produce a single 3D fabric capable of replacing many 2D fabrics or non-wovens currently and traditionally utilized. It requires producing a very thick 3D fabric, which would be able to compensate and even surpass the capabilities of existing 2D panels for soft body armour to dissipate the kinetic energy of the threats [2]. The advantage of these structures over the 2D structures is the fact that they can be produced using both conventional and 3D weaving machines. These are yarns in z-direction that hold together warps and wefts in these structures. Another advantage of this solution is the fact that yarns do not crimp and due to the structure they create, they allow a high longitudinal wave propagation after the contact with a projectile. One of the recognized producers of 3D structures for ballistics, 3Tex, developed production process and structures to create 3D fabrics for body and vehicle armour (3WEAVE® based on S2-Glass) [2, 60].

As it was mentioned in the text of this chapter, plain weave utilized in case of woven structures made of Kevlar yarn minimizes warps and wefts slippage; however, it also provides the highest crimp of the yarns, which as a consequence limits the propagation of the wave energy along the yarns. In 3D orthogonal structures, one observes a high yarn coverage and a low yarns crimp. There are some comments in the literature [2] saying that this type of element for soft body armour may replace currently popular multi-layer system of body protection; however, the author believes that orthogonal 3D structure for ballistics will be rather utilized in the future as an alternative but will not replace the traditional 2D structures due to cost of weaving machines for 3D structures, the fact of easiness to produce UD structures and a ballistic panel for soft body armour made of Kevlar woven fabrics, and finally, the fact that 2D structures are working perfectly well at this point.

10. Future trends

There are two major directions in which the development of ballistic protections can head. The first direction mentioned here is non-Newtonian fluids as an element supporting the existing ballistic panels in stopping the projectiles and as shock absorber element. The second direction is work on auxetic materials, which are materials having a negative Poisson's ratio.

10.1. Non-Newtonian fluids for liquid body armour

For a better understanding of this topic, it is suggested to start with an explanation what the Newtonian liquids are. The term Newtonian liquid was given after Sir Isaac Newton (1642–1726) who characterized the flow behaviour of fluids with a simple linear relation between

shear stress [mPa] and shear rate [1/s]. This relationship is now known to the world as Newton's Law of Viscosity where:

$$\tau = \eta\gamma, \tag{1}$$

where τ is a shear stress in Pascal [Pa], η is the viscosity of the fluid, in $(N \times s)/m^2 = [Pa \times s]$, which is Pascal-second, and γ is a shear rate. γ is the rate at which a progressive shearing is applied to the substance, measured in reciprocal seconds $[s^{-1}]$.

Liquid has a definite volume, but not a definite form [61]. A common property of liquid is that they can only transmit a pressure to solid or liquid surfaces bounding the liquid. Tangential forces on such surfaces will first occur when there is a relative motion between the liquid and the solid or liquid surface [60–62]. Such forces are frictional forces on the surface of bodies moving through air or water. When we study the flow of water in the bath or in a river, we can see that the flow velocity is greatest in the middle of the water or river and is reduced to zero at the edges of the bathtub or a riverbank. The phenomenon is explained by the notion of tangential forces, between the water layers that try to slow down the flow. The volume of flowing liquid is nearly constant. As a consequence, liquids are considered to be incompressible. A fluid is a material that deforms continuously when it is subjected to anisotropic states of stress. Usually, highly viscous fluids do not obey this linear law and therefore they belong to the *non-Newtonian fluids*. For non-Newtonian fluids in simple shear flow, a viscosity function is the following:

$$\eta(\gamma') = \frac{\tau}{\gamma}, \tag{2}$$

where: $\eta(\gamma')$ is called the apparent viscosity [Pa × s]; τ is shear stress [Pa].

In order to calculate the shear stress τ of the non-Newtonian fluids, one may apply the following formula:

$$\tau = \eta(\gamma')\gamma' \tag{3}$$

Shear thickening fluids (STFs) are characterized by an increase in viscosity when the shear rate increases achieves a critical value. The incorporation of STFs to Kevlar® fabrics is being investigated to improve ballistic protection capabilities as well as to enhance stab resistance. Shear thickening is defined in the British Standard Rheological Nomenclature as the increase of viscosity with increase in shear rate [60–63].

There are two main types of the non-Newtonian media: (1) fluids with the maximal (zero-shear-rate) Newtonian viscosity and (2) yielding viscoplastic materials. Numerous intermediate and superimposing situations can also exist [61–64].

10.2. Non-Newtonian substances

A popular non-Newtonian substance is a combination of polyethylene glycol (liquid phase) in combination with a silica powder (solid phase). The mixture contains billions of silica nanoparticles, more than 100 times finer than a human hair evenly distributed in the glycol.

In the liquid state, the particles have a weak molecular surface charge so they do not clamp together. However, when the object affects the liquid, it changes radically the state as its kinetic energy forces the particles to stick together in the lattice, which is a strong chemical bond called hydro-cluster. The liquid becomes as hard as ceramic for a very short period of time (parts of seconds). As soon as the kinetic energy is spent, the bond (lattice) is released and the solution becomes liquid again. The features of the mixture of polyethylene glycol and a silica powder are utilized to enhance abilities of ballistic protections, e.g. fabrics made of Kevlar are soaked in this mixture.

10.3. Auxetic materials

These are solid materials that have negative Poisson's ratio [65–67]. It means that when they are submitted to the stretch in the longitudinal direction, they expend latterly (get bulky or thicker) and when they are compressed, they are getting narrower in the direction perpendicular to the direction of the compressive force. This characteristic is due to the complex microstructure of these solid materials [64, 65]. Based on these structures present in nature, e.g. cristobalite or same selected human tissue, some man-made forms of auxetic structures are created, e.g. metallic, ceramic and foams. One of the typical and known examples of an auxetic foam [65, 67, 68], having high crack resistance [68]. Due to the extraordinary microstructure of these materials, the idea of imitating it and shaping textiles along the lines of this unique microstructure appeared. The liquid crystalline polymer (LCP) was developed with laterally attached rods in a main chain of this polymer [69]. The orientation of the laterally attached rods is parallel to the polymer chain axis. Under tensile stress, full extension of the polymer main chain forces is leading to an expansion in the direction normal to the chain axis and hence to auxetic behaviour. The auxetic fibres have great potential to be used in fibre-reinforced composites. Recently invented auxetic yarn [70] has the ability to response to external force and to the moisture present in the surrounding by using moisture-activated shrinking filament. The invented fibre is a combination of two components, one component is a moisture-sensitive shrinking filament with relatively high modulus of elasticity such as modified cellulosic fibres, e.g. cotton or rayon. The other component is an elastic material of lower modulus of elasticity. When the fibre is in wet state, the moisture-sensitive shrinking component shrinks and a pulling force is applied along to the elastic component causing it to deform and form helices. There were several different attempts to prepare fabrics based on the auxetic materials structure. Some studies have revealed that an auxetic effect can successfully be induced by using rotating units such as squares [71], rectangles [72]. An auxetic woven textile structure utilizing a double helix yarn in a composite material was produced [73]. The yarn was a reinforcement in the composite. Auxetic materials can also be used for vibration damping and shock absorbency in case of bomb blast curtains, which can open a large number of pores under tension allowing the shock wave through but leaving the curtains intact to catch glass and other debris. A commercially available product—Zetix™ helical-auxetic fibre technology is a perfect example an anti-ballistic application of auxetic structures into protective textiles. Zetix™ is used in a variety of products, including body armour and seat belts. XTEGRA [74] is another producer of auxetic textiles structures, which provides the fabrics for armour, blast panels and thermal protection systems. This type of protective materials utilizes a very modest amount of expensive high-performance fibres and a great amount of their cheap replacements.

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