

BALLISTIC-RESISTANT HELMET SHELL

DESCRIPTION

The present invention relates to a ballistic-resistant helmet.

5 Specifically it relates to a light-weight shell for a ballistic-resistant helmet.

Ballistic-resistant helmets having a shell comprising a consolidated stack of layers of uni-directionally aligned anti-ballistic fibers and a binder are known in the prior art. For example from WO2007/107359. A drawback with such helmets is that they can be heavy. In addition, modern uses of ballistic-resistant helmets involve the
10 addition of equipment such as communications equipment, goggles and night vision glasses. The total weight can make the helmet unnecessarily uncomfortable for the helmet wearer, particularly when wearing in challenging conditions or for long periods. A significant part of the weight of the helmet comes from the helmet shell itself.

An object of the present invention is to provide a ballistic-resistant
15 helmet which provides a high standard of ballistic protection but which is lighter than known helmet shells. A further object is to provide a helmet shell having a higher level of ballistic resistance.

Accordingly, the present invention provides a ballistic-resistant helmet shell which comprises a consolidated stack of layers of uni-directionally aligned anti-
20 ballistic fibers and a binder, characterized in that said ballistic-resistant helmet shell has an average thickness at the crown of from 3.5 to 5.5 mm; an average thickness at each of the front and back of from 4.5 to 6.5 mm; and an average thickness at the left and right of from 4.5 to 7.5 mm; and wherein the average thickness at the crown is less than the average thickness at the front.

25 The present invention also provides a ballistic-resistant helmet comprising a ballistic-resistant helmet shell.

A helmet shell is the basic structure of a helmet, and provides the ballistic resistance. The shell excludes linings, straps, fittings, decoration and accessories.

30 As used herein, a consolidated stack refers to multiple layers which are pressed together at elevated temperature to produce a single article.

The term layer of unidirectionally aligned anti-ballistic fibers and a binder refers to a layer of a fibrous network of unidirectionally oriented anti-ballistic fibers and a binder that basically holds the fibers together. The fibers are essentially
35 oriented in parallel to each other within the layer.

The term anti-ballistic fiber comprises not only a monofilament but, amongst others, also a multifilament yarn or a flat tape. The width of a flat tape is preferably between 2 mm and 100 mm, more preferably between 5 mm and 60 mm, most preferably between 10 mm and 40 mm. Thickness of a flat tape preferably is
5 between 10 μm and 200 μm , more preferably between 25 μm and 100 μm .

As used herein, average thickness is measured by taking three measurements from within the area defined (front, back, left, right, crown), each measurement spaced apart from the other measurements by at least 2 cm, and calculating the mean value.

10 Crown is defined as an area of 15 cm diameter from the top center of the helmet shell. The top center is the intersection of the sagittal and coronal planes. Front is defined as an area at the front of the helmet shell and no more than 5 cm from the sagittal plane and no more than 10 cm above the basic plane. Back is defined as an area at the rear of the helmet shell and no more than 5 cm from the sagittal plane
15 and no more than 10 cm above the basic plane. Left is defined as an area at the left side of the helmet shell and no more than 7.5 cm from the coronal plane and no more than 5 cm above the basic plane. Right is defined as an area at the right side of the helmet shell and no more than 7.5 cm from the coronal plane and no more than 5 cm above the basic plane. The definitions for front, back, left and right correspond to the
20 target areas for NIJ-0106-01.

Such a helmet shell may be produced by a process of stacking multiple layers comprising unidirectionally oriented anti-ballistic fibers and a binder whereby in the stack, the fiber direction in a layer is at an angle α to the fiber direction in an adjacent layer. Typically, α is between 5 and 90°, more preferably between 45
25 and 90° and most preferably between 75 and 90°.

To produce the helmet shell the stack is placed in an open mould, consisting of a female and a male part, and subsequently the stack is clamped to one part of the mould, generally the female part. This clamping is done through a so-called control member and is done in such a way that the stack is fixed in its position towards
30 the said female mould part, but that the stack can still slip and move during the closing of the mould, i.e. when moving of the male part into the female mould part. This clamping through the control member may suitably be done by pressing the stack at its outer regions against the female mould part. The force with which the control member is clamped to one part of the mould preferably ranges between 50 and 5000 N, more

preferably between 100 and 3000 N and can be optimized by a skilled person through some routine experimentation.

After the stack is clamped to one part of the mould, the mould is closed e.g. by moving the male part into the female mould part and the stack is consolidated under temperature and pressure into the shape of a helmet shell. The consolidated stack is preferably cooled in the mould, still under pressure. As soon as the consolidated stack has cooled to a temperature, typically of 80 °C or 50 °C, the mould can be opened and the consolidated stack is released from the mould. Moreover the consolidated stack may further be processed through known mechanical techniques as sawing, grinding, drilling to the desired final dimensions.

The temperature during consolidation is chosen below the temperature at which the anti-ballistic fiber loses its high mechanical properties due to e.g. melting. In the case of e.g. HPPE fibers, often having a melting temperature of 155 °C, a mould temperature below 135 °C is generally used. The minimum temperature generally is chosen such that a reasonable speed of consolidation is obtained. In this respect 50 °C is a suitable lower temperature limit, preferably this lower limit is at least 75 °C, more preferably at least 95 °C, most preferably at least 115 °C.

The pressure during consolidating is typically at least 7 MPa, more preferably at least 10 MPa, even more preferably at least 15 MPa and most preferably at least 20 MPa. In this way a better anti-ballistic performance is achieved. Optionally this consolidating may be preceded by a low pressure pre-shaping step. Pressure during this pre-shaping step may vary between 2 and 5 MPa. After pre-shaping and before consolidating the mould may be opened and the occurrence of blisters may be verified, which may subsequently be removed by e.g. piercing with a sharp object. Other options to prevent blisters include degassing during moulding or use of vacuum.

The optimum time for consolidation generally ranges from 5 to 120 minutes, depending on conditions such as temperature, pressure and part thickness and can be verified through routine experimentation. Typically the consolidation time is less than 90 minutes; and preferably less than 60 minutes.

A helmet shell as described may have very good anti-ballistic properties in relation to its weight. Typically, a helmet shell of the present invention can stop 9mm FMJ (full metal jacket) ammunition above 380 m/s; preferably above 400 m/s; more preferably above 420 m/s. Further, the helmet shell of the present invention may have a V_{50} of at least 800 m/s against 1.1 g FSP (fragment simulating projectile); preferably at least 850 m/s; more preferably above 900 m/s.

An advantage of such a helmet shell is that it is very light. Typically such a helmet shell has a mass below 800 g. Preferably it has a mass of from 650 to 750 g. More preferably, it has a mass of from 680 to 730 g.

5 The helmet shell may be of any suitable design. For example it may be PASGT, MICH or other design known in the art. In order to achieve particularly low weight, the ballistic-resistant helmet shell is suitable for the modular integrated communications helmet (MICH) design. In particular, it may be suitable for a MICH design modified for Asian head shape. Such modification is known in the art and involves a higher left-right:front-back distance ratio than standard MICH design. A particularly low weight design is the MICH high-cut design. This typically has a mass of from 500 to 650 g; more preferably from 550 to 600 g. Helmet shells typically are produced in small medium and large sizes. References herein are preferably to medium size helmet shells. A large helmet shell may be approximately 3, 5, 7 or even 10% larger. A small helmet shell may be approximately 3, 5, 7 or even 10% smaller.

15 Typically, in the ballistic-resistant helmet shell, the average thickness at the front and back is greater than the average thickness at the left and right.

The ballistic-resistant helmet shell has an average thickness at the crown of from 3.5 to 5.5 mm. Typically the average thickness at the crown is from 4 to 5 mm. Preferably, the average thickness at the crown is about 4.5 mm.

20 The ballistic-resistant helmet shell has an average thickness at each of the front and back of from 4.5 to 6.5 mm. Typically, the average thickness at each of the front and back is from 5 to 6 mm. Preferably, the average thickness at the each of the front and back is about 5.5 mm.

The ballistic-resistant helmet shell has a thickness at the left and right of from 4.5 to 7.5 mm. Typically, the average thickness at each of the left and right is from 5 to 7 mm. Preferably, the average thickness at each of the left and right is from 5.5 to 6.5 mm; most preferably about 6 mm.

The anti-ballistic fibers in the invention may be inorganic or organic fibers.

30 Suitable inorganic fibers are, for example, glass fibers, carbon fibers and ceramic fibers. Preferably the inorganic fibers are carbon fibers produced from polyacrylonitrile.

Suitable organic fibers with such a high tensile strength are, for example, aromatic polyamide fibers (so-called aramid fibers), especially poly(p-phenylene teraphthalamide), liquid crystalline polymer and ladder-like polymer fibers

35

such as polybenzimidazoles or polybenzoxazoles, esp. poly(1,4-phenylene-2,6-benzobisoxazole) (PBO), or poly(2,6-diimidazo[4,5-b-4',5'-e]pyridinylene-1,4-(2,5-dihydroxy)phenylene) (PIPD; also referred to as M5) and fibers of, for example, polyolefins, polyvinyl alcohol, and polyacrylonitrile which are highly oriented, such as
5 obtained, for example, by a gel spinning process.

Suitable polyolefins are in particular homopolymers and copolymers of ethylene and propylene, which may also contain small quantities of one or more other polymers, in particular other alkene-1-polymers.

Good results are obtained if linear polyethylene (PE) is selected as
10 the polyolefin. Linear polyethylene is herein understood to mean polyethylene with less than 1 side chain per 100 C atoms, and preferably with less than 1 side chain per 300 C atoms; a side chain or branch generally containing at least 10 C atoms. The linear polyethylene may further contain up to 5 mol% of one or more other alkenes that are copolymerisable therewith, such as propene, butene, pentene, 4-methylpentene,
15 octene. Preferably, the linear polyethylene is of high molar mass with an intrinsic viscosity (IV, as determined on solutions in decalin at 135°C) of at least 4 dl/g; more preferably of at least 8 dl/g. Such polyethylene is also referred to as ultra-high molecular weight polyethylene. Intrinsic viscosity is a measure for molecular weight that can more easily be determined than actual molar mass parameters like M_n and M_w .
20 There are several empirical relations between IV and M_w , but such relation is highly dependent on molecular weight distribution. Based on the equation $M_w = 5.37 \times 10^4 [IV]^{1.37}$ (see EP 0504954 A1) an IV of 4 or 8 dl/g would be equivalent to M_w of about 360 or 930 kg/mol, respectively. Preferably, the anti-ballistic fibers are ultra-high molecular weight polyethylene.

25 Preferably the anti-ballistic fibers have a tensile strength of at least about 1.2 GPa and a tensile modulus of at least 40 GPa. More preferably, the fibers have a tensile strength of at least 2 GPa, more preferably at least 2.5 GPa or most preferably at least 3 GPa. The advantage of these fibers is that they have very high tensile strength, so that they are in particular very suitable for use in lightweight
30 ballistic-resistant articles.

The term binder refers to a material that binds or holds the fibers together in the sheet comprising mono-layers of unidirectional oriented fibers and a binder, the binder may enclose the fibers in their entirety or in part, such that the

structure of the mono-layer is retained during handling and making of preformed sheets.

In a preferred embodiment, the binder is a polymeric matrix material, and may be a thermosetting material or a thermoplastic material, or mixtures of the two. In the case the matrix material is a thermosetting polymer vinyl esters, unsaturated polyesters, epoxies or phenol resins are preferably selected as matrix material. In the case the matrix material is a thermoplastic polymer polyurethanes, polyvinyls, polyacrylics, polyolefins or thermoplastic elastomeric block copolymers such as polyisopropene-polyethylene-butylene-polystyrene or polystyrene-polyisoprene-polystyrene block copolymers are preferably selected as matrix material. Preferably the binder consists of a thermoplastic polymer, which binder preferably completely coats the individual filaments of said fibers in a mono-layer, and which binder has a tensile modulus (determined in accordance with ASTM D638, at 25° C) of at least 75 MPa, more preferably at least 150 MPa and even more preferably at least 250 MPa, most preferably of at least 400 MPa. Preferably the binder has a tensile modulus of at most 1000 MPa. Such a binder results in high flexibility of a sheet comprising a mono-layer, and of a high enough stiffness in a consolidated stack. Preferably, the binder is polyurethane.

Typically, the amount of binder in the helmet shell is at most 30 mass%, more preferably at most 25, or 20% of the mass of the helmet shell. Preferably, the binder is present in an amount of from 12 to 20 % by weight of the helmet shell. More preferably, it is present in an amount of from 13 to 18 %; most preferably around 15 to 16 %. This results in the best ballistic performance. In the case that the anti-ballistic fibers are tapes, the amount of binder may be lower still, for example at most 7, 5 or even at most 3 % of the mass of the helmet shell.

Optionally the helmet shell of the present invention may comprise at least one layer comprising a second anti-ballistic fiber and a binder. This layer may be placed on the inner or outer surface of the stack of layers, or between two layers of the stack or a combination of the two, for example alternating with the layers of unidirectionally aligned anti-ballistic fiber and a binder. The second anti-ballistic fiber may be chosen from the earlier listed range of anti-ballistic fibers. The layer of the second anti-ballistic fiber may comprise a binder chosen from the earlier listed polymers. Preferably the unidirectionally aligned anti-ballistic fiber is an organic fiber and the second anti-ballistic fiber is an inorganic fiber. Most preferably, the second anti-ballistic fiber is carbon fiber.

Preferably, the layer comprising a second anti-ballistic fiber and a binder is close to or at the outer surface (or strike face) of the helmet shell of the present invention. The strike face of the shaped part is the side of the product facing the ballistic impact. The layer comprising a second anti-ballistic fiber may be smaller
5 than the surface area of the helmet shell. For example it may only be present through a cross section of part of the helmet. For example, it may take the form of a small disk, located close to the crown. Alternatively, it may be an open circle or annular ring present at the front, back and sides of the helmet shell but not at the crown. An advantage hereof is that a shaped part, e.g. in the form of a helmet, as obtained with
10 the process according to the invention gives a higher stiffness in the sideways direction. This means that a person wearing such helmet has a further improved side protection of e.g. his ears upon impact.

Typically, the helmet shell of the present invention further comprises at least one layer of carbon fiber. Preferably, the at least one layer of carbon fiber is
15 located close to or at the outer surface of the helmet shell. A layer of carbon fiber comprises woven or non-woven, including unidirectional oriented, carbon fibers and a binder, said binder being chosen from those listed previously.

In a preferred embodiment of the process according to the invention the anti-ballistic fiber or the second the anti-ballistic fiber in at least one of the layers
20 closest to the strike face is embedded in a thermoset matrix.

The helmet shell may further comprise a coating. For example a coating imparting impact resistance ease of decoration or ease of release from the mould. The coating could be polyamide or polyethylene. Typically, a helmet shell of the present invention further comprises on the outside surface a coating comprising
25 polyurea, for example, Paxcon® available from Line-X®, Huntsville, Alabama, USA.

FIG. 1 illustrates a MICH type helmet design. The preferred helmet design for the present invention.

Test methods as referred to in the present application, are as follows:

IV: the Intrinsic Viscosity is determined according to method ASTM
30 D1601 at 135°C in decalin, the dissolution time being 16 hours, with DBPC as anti-oxidant in an amount of 2 g/l solution, by extrapolating the viscosity as measured at different concentrations to zero concentration;

Side chains: the number of side chains in a UHMWPE sample is determined by FTIR on a 2 mm thick compression moulded film, by quantifying the

absorption at 1375 cm^{-1} using a calibration curve based on NMR measurements (as e.g. in EP 0269151);

Tensile properties (measured at $25\text{ }^{\circ}\text{C}$): tensile strength (or strength) and tensile modulus (or modulus) are defined and determined on multifilament yarns as specified in ASTM D885M, using a nominal gauge length of the fiber of 500 mm, a crosshead speed of 50%/min. On the basis of the measured stress-strain curve the modulus is determined as the gradient between 0.3 and 1% strain. For calculation of the modulus and strength, the tensile forces measured are divided by the titre, as determined by weighing 10 metres of fiber; values in GPa are calculated assuming a density of 0.97 g/cm^3 .

V_{50} 1.1g FSP was determined in accordance with MIL-STD-662f (1997): Shooting was performed using 1.1 gram Fragment simulating projectiles (FSP). Shooting was performed with an intended FSP speed being about equal to the expected V_{50} (680 meters/second). The actual FSP speed was measured before impact. In case a perforation occurred, the speed of the next shot was reduced with an anticipated amount of 15 m/second (it should be noted that accurate setting of the FSP speed on forehand is not possible. The amount of explosive and the way of charging allow an estimated setting of the speed only. However the measurement of the speed before impact is very accurate. In case the projectile was stopped, the next intended FSP speed was increased with 15m/second. Each helmet was subjected to eight shots around the rim of the helmet at about equal distance of each other and at a distance of about 6 cm of the edge of the helmet (edge effects are thus excluded). The final V_{50} was determined as the average of the three highest speeds with a stop, and the three lowest speeds yielding a perforation. The same numbers are used for calculating the standard deviation. Other shots were considered to be too far from V_{50} for being relevant and, as such, these results were neglected.

V_{STOP} 9mm FMJ was carried out in accordance with NIJ 0106.01 level IIA & level II. The helmet shell was fitted with accessories, including straps, padding and external equipment fitting but no coating and subjected to ballistic testing. Shooting was performed using 9mm 124 grain FMJ. Shooting was performed with an intended speed being about equal to the expected V_{STOP} (436 meters/second). The actual projectile speed was measured before impact. Each helmet was subjected to four shots V_{STOP} was determined as the average of the three highest speeds with a stop. The same numbers are used for calculating the standard deviation.

EXAMPLE

A helmet shell was made according to the following process:

A square shaped stack with dimensions of 53 cm x 53 cm was formed of 80 layers of unidirectionally aligned ultra-high molecular weight polyethylene fiber in a 17 wt% polyurethane matrix, whereby the fiber direction in each mono-layer is at an angle of 90 ° with respect to an adjacent monolayer. The material was 40 layers of HB210 from DSM Dyneema, Geleen, the Netherlands. The areal density of the stack was 5.5 kg/m². The stack was clamped in position over the female part of a helmet mould. Areal density is measured with respect to the outside surface of the helmet shell.

A clamping pressure of about 2000N was applied to the control member such that the stack was flat and fixed in its position towards the said female mould part, but that the stack could still slip and move during the closing of the mould. The mould was closed by inserting the male part into the female part of the mould whereby the flat stack slowly was positioned against the female mould surface. This closing was done in a time span of 5 minutes in order to have a temperature transfer from the male and female mould part to the stack. The temperature of the mould was about 130 °C. The applied pressure was 2 MPa and the stack was retained in the mould until the temperature at the centre of the stack was 130 °C. The system was degassed 3 times while at 2 MPa and left for 5 minutes. Subsequently, the pressure was increased to a compressive pressure of about 25 MPa, and the stack was kept under this pressure for 15 minutes at 130 °C. Next, the stack was cooled to a temperature of 50°C over a period of 30 minutes at the same compressive pressure. Subsequently the mould was opened and debris was cut from the helmet to obtain a smooth helmet edge.

The resulting helmet shell was weighed, and average thickness was measured as described above, using a non-destructive modified vernier caliper system. The helmet shell was tested for V₅₀ against 1.1g FSP according to MIL-STD-662f (1997). The helmet accessories were added and V_{STOP} against 9mm FMJ according to NIJ 0106.01 as described above. Results are shown in Table 1.

Table 1

Weight of helmet shell [g]	Average thickness front [mm]	Average thickness back [mm]	Average thickness left [mm]	Average thickness right [mm]	Average thickness crown (estimated) [mm]	V ₅₀ 1.1g FSP MIL-ST-662f (1997) [m/s]	V _{STOP} 9mm FMJ NIJ 0106.01 (helmet with accessories) [m/s]
685	6.07	5.74	6.15	6.55	≤ 5	917.8 +/- 30	436 +/- 30

The results indicate that a helmet shell of the present invention with a weight lower than 700 g can stop 9mm FMJ at 436 m/s. Further, surprisingly, the helmet shell of the present invention has a V₅₀ of over 900m/s against 1.1 g FSP.

CLAIMS

1. A ballistic-resistant helmet shell which comprises a consolidated stack of layers of uni-directionally aligned anti-ballistic fibers and a binder,
5 characterized in that said ballistic-resistant helmet shell has an average thickness at the crown of from 3.5 to 5.5 mm; an average thickness at each of the front and back of from 4.5 to 6.5 mm; and an average thickness at the left and right of from 4.5 to 7.5 mm; and wherein the average thickness at the crown is less than the average thickness at the front.
- 10 2. A ballistic-resistant helmet shell according to claim 1, which has a mass of from 650 to 750 g.
3. A ballistic-resistant helmet shell according to claim 2, which has a mass of from 680 to 730 g.
4. A ballistic-resistant helmet shell according to any one of claims 1 to 3, which is
15 suitable for the modular integrated communications helmet (MICH) design.
5. A ballistic-resistant helmet shell according to any one of claims 1 to 3, wherein the average thickness at the front and back is greater than the average thickness at the left and right.
6. A ballistic-resistant helmet shell according to any one of claims 1 to 3, wherein
20 the average thickness at the crown is from 4 to 5 mm.
7. A ballistic-resistant helmet shell according to any one of claims 1 to 3, wherein the average thickness at each of the front and back is from 5 to 6 mm.
8. A ballistic-resistant helmet shell according to any one of claims 1 to 3, wherein the average thickness at each of the left and right is from 5 to 7 mm.
- 25 9. A ballistic-resistant helmet shell according to any one of claims 1 to 3, wherein the fibers are ultra-high molecular weight polyethylene.
10. A ballistic-resistant helmet shell according to any one of claims 1 to 3 wherein the binder is polyurethane.
11. A ballistic-resistant helmet shell according to any one of claims 1 to 3 wherein
30 the binder is present in an amount of from 12 to 20 % by weight of the helmet shell.
12. A ballistic-resistant helmet shell according to any one of claims 1 to 3, which further comprises at least one layer of carbon fiber.
13. A ballistic-resistant helmet shell according to any one of claims 1 to 3, which
35 further comprises on the outside surface a coating comprising polyurea.

14. A ballistic-resistant helmet comprising a ballistic-resistant helmet shell as defined in any one of claims 1 to 3.