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(54) **HELMET CONTAINING POLYETHYLENE FIBERS**

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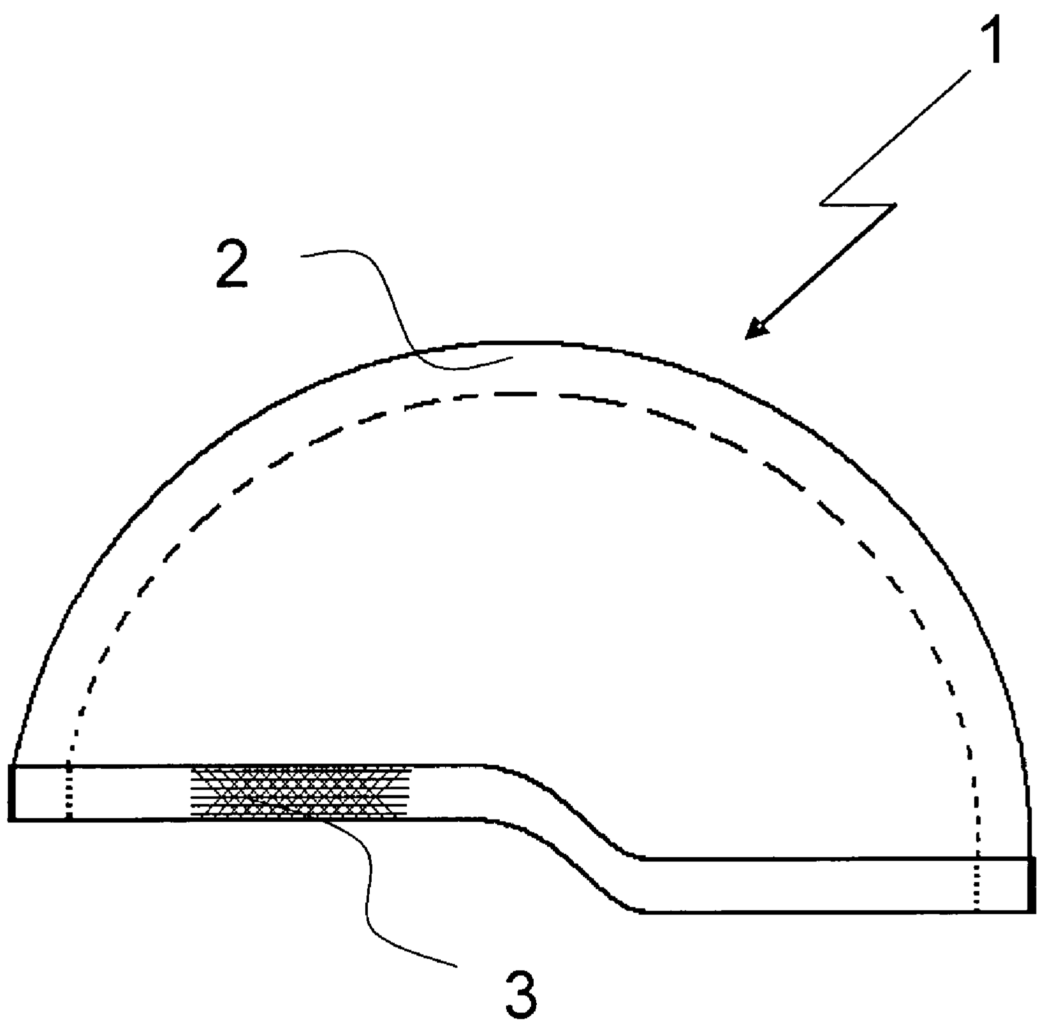
(57) **ABSTRACT**

An anti-ballistic helmet (**1**) having a shell (**2**) containing mono-layers of uni-directional ultrahigh molecular weight polyethylene (UHMwPE) fibers, the shell is at its rim being connected to a reinforcing profile (**3**).



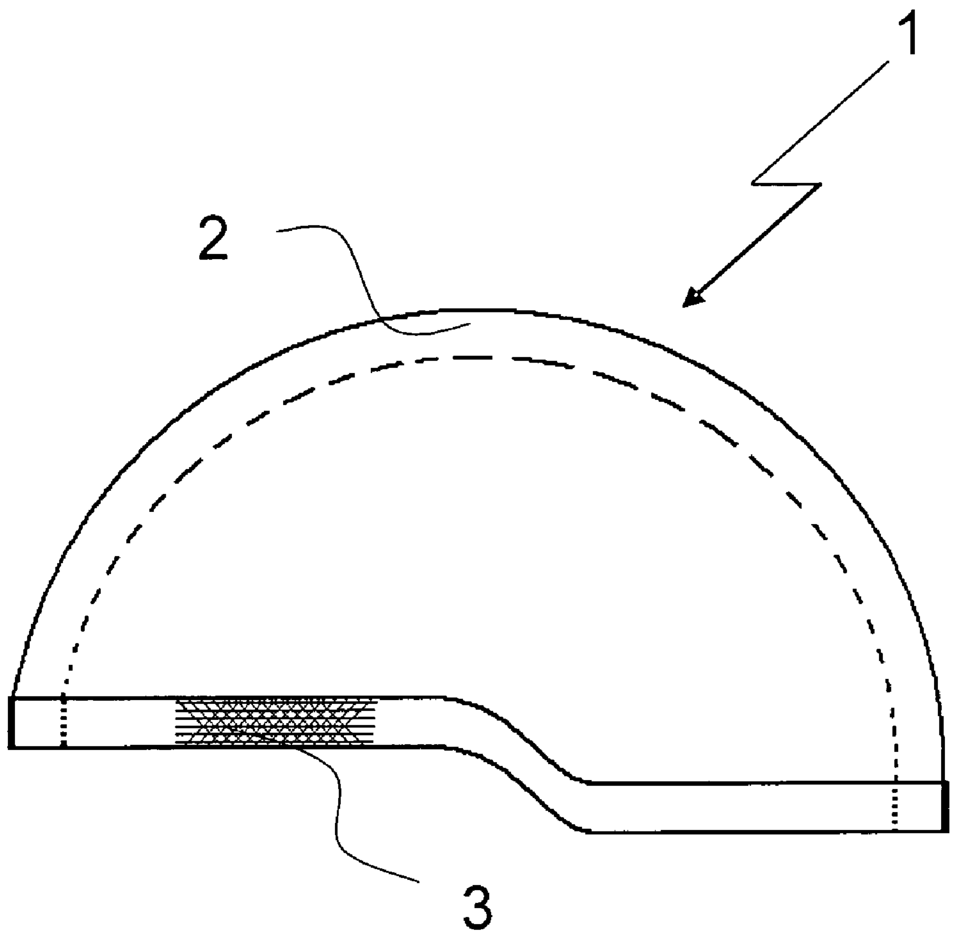


Fig. 1

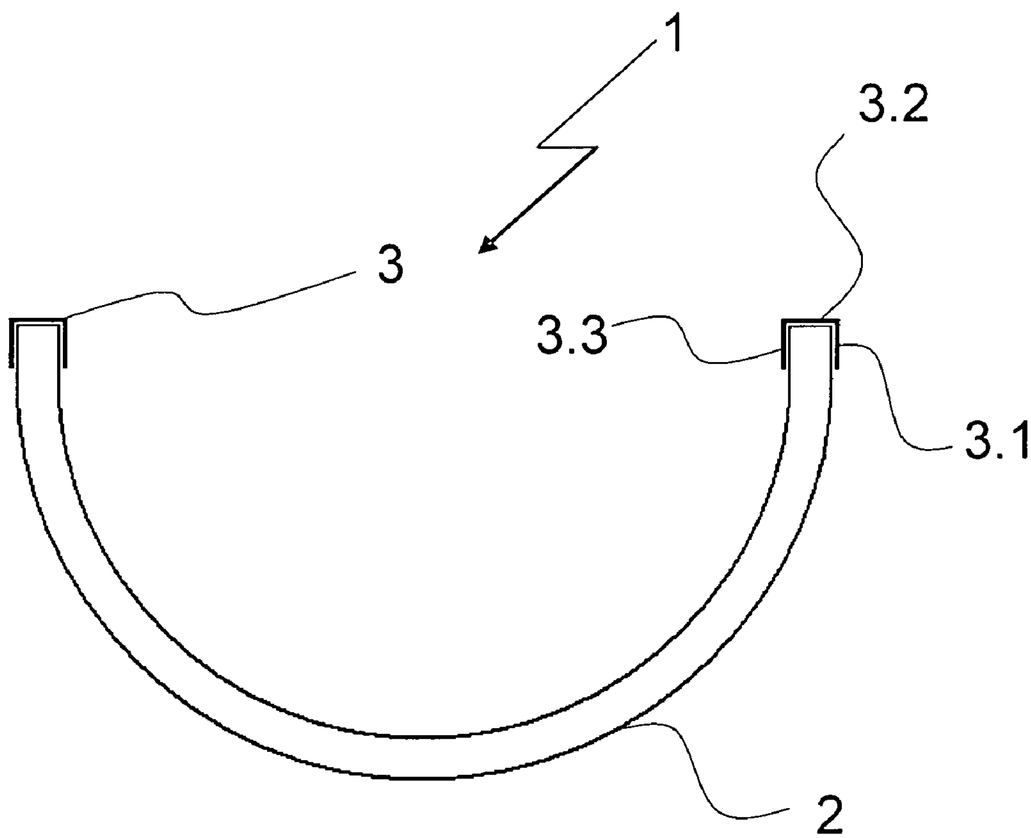


Fig. 2

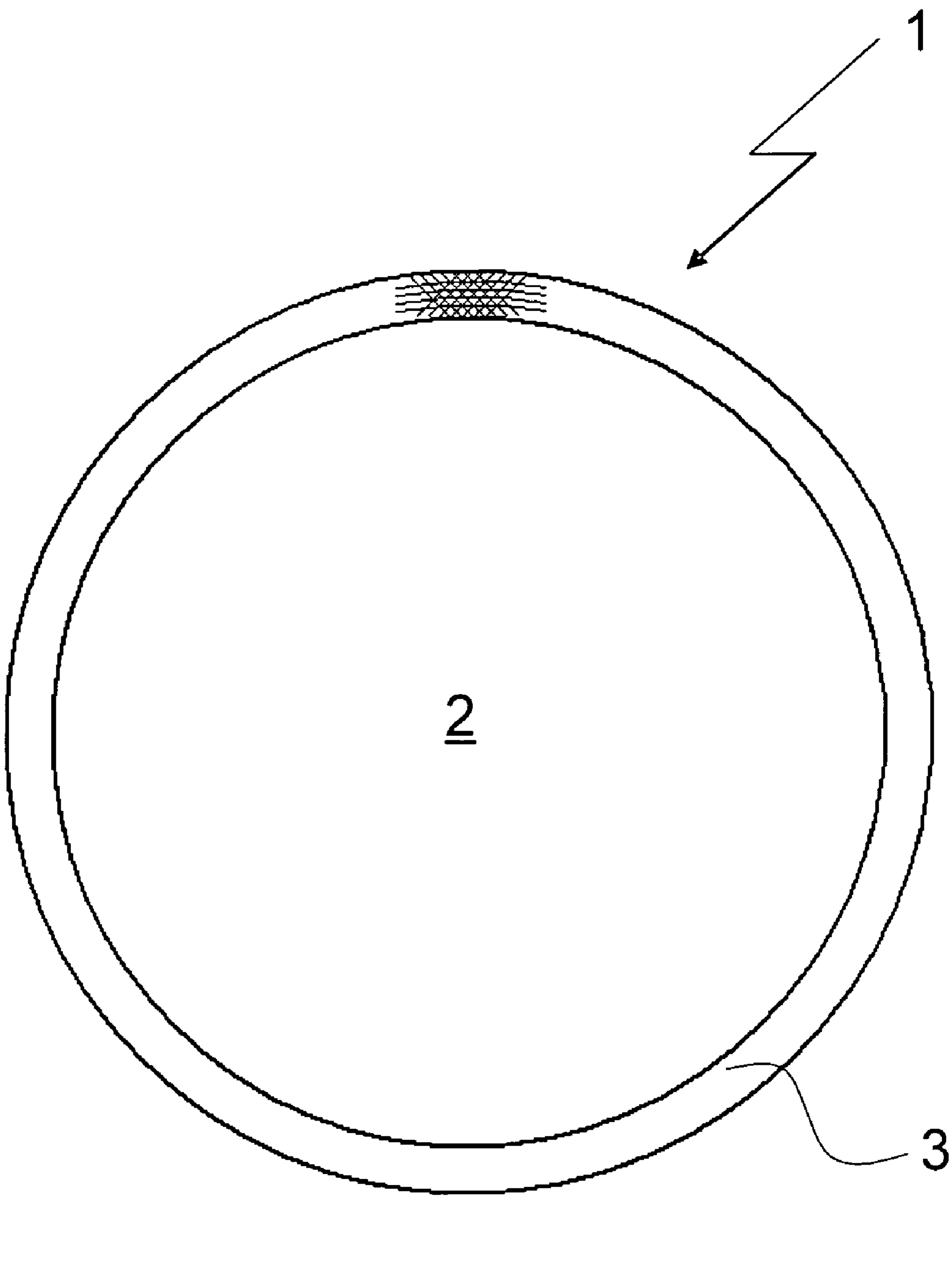


Fig. 3

HELMET CONTAINING POLYETHYLENE FIBERS

[0001] The invention relates to an anti-ballistic helmet having a shell containing mono-layers of uni-directional ultra-high molecular weight polyethylene (UHMwPE) fibers.

[0002] An anti-ballistic helmet, unless otherwise specified hereinafter simply called helmet, is known from U.S. Pat. No. 4,613,535. In U.S. Pat. No. 4,613,535 shaped parts are described containing mono-layers of uni-directional UHMwPE fibers and a binder. Examples of the shaped parts include ballistic articles like helmets. The shaped parts are provided with at least one additional rigid layer on a major surface of the parts, to produce a part having increased rigidity.

[0003] One of the main problems in developing helmets is to obtain weight reduction. In view of known steel helmets, the introduction of a composite helmet was an important step forward in weight reduction. Improvements in the design and the materials used have brought further weight reductions. However there is still a need for further weight reduction, without sacrificing on ballistic protection, service life and damage tolerance of the helmet. For example for air born troops it is very important to keep the total head-load below acceptable limits, while in the same time troopers are more and more equipped with for example communication equipment, night viewer etc., attached to their helmets which consequently add weight.

[0004] In most instances the way of finding the solution was in providing complex composite structures, combining different types of layers. One example is the above-mentioned U.S. Pat. No. 4,613,535. Another example is the helmet disclosed in WO961478 and also in 'Hybridized thermoplastic aramids enabling material technology for future force headgear' by S. M. Walsh, B. R. Scott, D. M. Spagnuolo and J. P. Wolbert of the US Army Research Laboratory Weapons & Materials Research Directorate Aberdeen Proving Ground as presented at the SAMPE 2005 conference, wherein it is said that the most promising structure is a shell containing an aramid composite layer as base layer and a hard layer as a skin containing carbon fibers and epoxy.

[0005] Aim of the invention is to provide a helmet having a low total weight and yet providing adequate protection against ballistic impacts, while furthermore this helmet has a good durability.

[0006] Surprisingly this aim is fulfilled by a helmet having a shell containing mono-layers of uni-directional UHMwPE fibers and preferably a binder, wherein at its rim the helmet shell is connected to a reinforcing profile. The function of the binder is to hold the fibers together. However, instead of applying a binder, the fibers can also be connected by pressing with a sufficiently high pressure at sufficiently high temperature.

[0007] It is unexpected that by applying a reinforcing profile to the rim of the shell adequate ballistic protection is obtained against impacts in parts of the helmet remote from the rim, so that it is possible to produce a helmet having a low weight and still a good durability. Although a helmet having an additional rigid layer over the surface of its shell is not excluded from the scope of the present invention, it is even possible to produce a helmet without this rigid layer that is often applied in composite helmets.

[0008] A safety helmet having an inner rigid layer provided with a reinforcing rim and an outer layer which is preferably made of high density foam is known from Australian Patent Application No. 2005/202254 A1. However, the safety helmet disclosed therein is only suitable as a construction or sports helmet and is clearly not suitable as an anti-ballistic helmet. The protection mechanisms provided by such a helmet construction is obviously not suitable to be used against bullets where other mechanisms of dissipating the bullet energy are needed. Although the inner rigid layer is provided with a reinforcing rim, the referred application mentions no advantages which directly or even remotely associate the presence of the reinforcing rim to anti-ballistic properties.

[0009] The invention is further explained in the drawings, without being limited to the embodiments exemplified in these drawings. In these drawings,

[0010] FIG. **1** shows a side view of helmet according to the invention.

[0011] FIG. **2** shows an intersection of a helmet according to the invention.

[0012] FIG. **3** shows a view on the helmet from the bottom.

[0013] FIG. **1** shows a helmet (**1**), containing a shell (**2**), the shell containing the mono-layers of uni-directional fibers and preferably a binder. At its rim the shell is connected to a reinforcing profile (**3**). The profile has a preferred fiber orientation with fibers in the profile direction and fibers in an angle of 45° and −45° with the profile direction.

[0014] FIG. **2** shows an intersection of a helmet (**1**) according to the invention, containing a shell (**2**) and a reinforcing profile (**3**), the reinforcing profile being U-shaped. The shell fits between the legs of the U-shaped profile and is connected to the profile at the surfaces (**3.1**), (**3.2**) and (**3.3**) of the profile.

[0015] FIG. **3** shows a helmet (**1**) according to the invention having a shell (**2**) and a reinforcing profile (**3**).

[0016] Preferably, the shell of the helmet of the invention comprises mono-layers of unidirectional UHMwPE fibers and a binder.

[0017] According to the invention the term mono-layer of unidirectional UHMwPE fibers and preferably a binder refers to a layer of a fibrous network of unidirectional oriented UHMwPE fibers and preferably a binder that basically holds the fibers together. The term unidirectional oriented fibers refer to fibers in one plane that are essentially oriented in parallel.

[0018] The term fiber comprises not only a monofilament but, inter alia, also a multifilament yarn or a tape. Width of the tape preferably is between 2 mm and 100 mm, more preferably between 5 mm and 60 mm, most preferably between 10 mm and 40 mm. Thickness of the tape preferably is between 10 μm and 200 μm, more preferably between 25 μm and 100 μm.

[0019] The UHMwPE fibers in the mono-layers of the helmet of the invention preferably have a tensile strength of at least about 1.2 GPa and a tensile modulus of at least 40 GPa. The fibers more preferably have a tensile strength of at least 2 GPa, even more preferably at least 2.5 GPa or most preferably at least 3 GPa. The advantage of these high strength fibers is that they are very suitable for use in lightweight ballistic-resistant articles.

[0020] Good results are obtained if linear UHMwPE is used. Linear UHMwPE 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, octene. Preferably, the linear polyethylene is of high molar mass with an intrinsic viscosity (IV, as determined on solutions in decalin at 135° C. according to the test method presented hereinafter) of at least 4 dl/g; more preferably of at least 8 dl/g. 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. There are several empirical relations between IV and M_w, but such relation is highly dependent on molecular weight distribution. Based on the equation $M_w=5.37\times10^4$ $[IV]^{1.37}$ (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.

[0021] UHMwPE fibers prepared by a gel spinning process, such as described, for example, in GB 2042414 A or WO 2001/73173 are preferably used. This results in a very good ballistic-protection/weight performance. A gel spinning process essentially consists of preparing a solution of a linear polyethylene with a high molar mass, spinning the solution into filaments at a temperature above the dissolving temperature, cooling the filaments to below the gelling temperature, such that gelling occurs, and stretching the filaments before, during or after the removal of the solvent.

[0022] In a preferred embodiment of the invention, the shell of the helmet comprises mono-layers of unidirectional oriented UHMwPE fibers, said mono-layers being grouped in at least two sheets. A sheet preferably contains at least two mono-layers. The mono-layers in a sheet may be positioned at an angle with respect to each other, the angle varying from 0 to 90°. The sheets may also be positioned at an angle with respect to each other.

[0023] The term binder refers also to a material that binds or holds the uni-directional 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. The binder may be applied in various forms and ways; for example as a film (by melting hereof at least partially covering the UHMwPE fibers), as a transverse bonding strip or as transverse fibers (transverse with respect to unidirectional fibers), or by impregnating and/or embedding the fibers with a matrix material, e.g. with a polymer melt, a solution or a dispersion of a polymeric material in a liquid. Preferably, matrix material is homogeneously distributed over the entire surface of the mono-layer, whereas a bonding strip or bonding fibers may be applied locally. Suitable binders are described in e.g. EP 0191306 B1, EP 1170925 A1, EP 0683374 B1 and EP 1144740 A1.

[0024] 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. The elongation at break of the matrix material is preferably greater than the elongation of the fibers. The binder preferably has an elongation of 2 to 600%, more preferably an elongation of 4 to 500%. Suitable thermosetting and thermoplastic matrix materials are enumerated in, for example, WO 91/12136 A1 (pages 15-21). 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. The binder should be chosen such to result in a high flexibility of the sheet comprising mono-layers, while the shell compressed from said sheets have a high enough stiffness.

[0025] Preferably, the amount of binder in the mono-layer is at most 30 mass %, more preferably at most 25, 20, or even at most 15 mass %. This results in the best anti-ballistic performance.

[0026] Good results are obtained if the direction of orientation of the fibers in adjacent mono-layers is at an angle of between 5 and 90°, preferably between 45 and 90°, most preferably between 75 and 90°.

[0027] Very good results for the helmet of the invention are obtained when the direction of orientation of the UHMWPE fibers in the mono-layers is at an angle towards the rim of the helmet. Preferably, the direction of orientation of the fibers in mono-layers in the shell are at an angle of between +30 and +60 respectively −30 ° and −60° towards the rim of the helmet. More preferably this angle is between +40 and +50°, respectively −40 and −50°, most preferably +45° or about 45°, respectively −45° or about −45°.

[0028] The shell may still contain a hard top layer, e.g. a metal or ceramic strike face, or a hard composite top layer, e.g. a woven glass fiber fabric impregnated with a thermosetting resin. However, preferably such a layer is not present, so that the most optimal helmet with respect to weight, anti-ballistic protection and durability is obtained. The term durability will be explained below.

[0029] The reinforcing profile may be produced from all kind of light-weight materials having a high stiffness and strength. Good examples include metals like steel, titanium, aluminum, magnesium and their alloys. Preferably the reinforcing profile is produced from a composite, containing reinforcing fibers and a second binder. The composite may contain all kind of reinforcing fibers, for example organic fibers such as aramid fibers. More preferable the composite contains inorganic fibers as e.g. ceramic fibers, glass fibers, basalt or silicon carbide fibers. In general, such fibers contain at least 15% silicon. Most preferably the composite contains carbon fibers. If a composite is chosen, the number orientations of the reinforcing fiber are at least two. More preferred are at least three fiber orientations. Suitable orientations may be 0°, 90°, +45°, and −45° with the direction of the reinforcing profile, as is illustrated in FIG. **1**, item (**3**). Most preferably the fibers are orientated at 0°, +45°, and −45° with the profile direction. The fibers in the composite may be woven or unidirectionally aligned, according to the mentioned fiber directions.

[0030] The second binder in the composite of the reinforcing profile should preferably show a reasonable adhesion to the fibers and a modulus of preferably at least 1400 MPa. The amount of second binder is preferably between 20 and 70% by volume, more preferably between 35 and 55% by volume.

[0031] Preferably the reinforcing profile has a compressive yield stress of at least 2 times the compressive yield stress of the shell, more preferably at least 4 times, most preferably at least 6 times the compressive yield of the shell. The compressive yield stress is measured by ASTM D 6641(issued in 2001). In case of a reinforcing rim comprising elongated reinforcing elements, e.g. fibers, the compressive yield stress must be measured in the direction of those said reinforcing elements which are positioned along the rim. It was observed that by a reinforcing rim having the required compression yield stress provides the helmet of the invention with improved anti-ballistic properties, in particular the anti-ballistic properties at locations remote from the rim are improved. Another advantage is that such a helmet has even further improved durability.

[0032] The reinforcing profile may have a cross section with all kind of shapes as for example L-shaped or U-shaped. Preferably the reinforcing profile has a U-shape. Furthermore the U-shaped profile may be connected easy and secure to the shell, if the shell fits into the U-shaped profile.

[0033] The reinforcing profile is connected to the shell of the helmet at the rim of said shell. By connected is herein understood that the reinforcing profile is fixated onto the shell of the helmet such that forces acting on the shell can be effectively transferred to and attenuated by the reinforcing profile and vice-versa.

[0034] The reinforcing profile may be connected to the shell of the helmet according to any known method in the art. A suitable example include gluing with a suitable adhesive, fixation by heat or simply by approaching the lateral sides of a U-shaped profile until a good fixation on the shell is achieved.

[0035] Good connections are achieved when the part of the reinforcing rim that overlaps with the lateral side of the shell of the helmet has a length of preferably at least 0.5 times the thickness of the shell, said thickness being measured at the bottom of the shell of the helmet, more preferably at least 1 times, most preferably at least 2 times said thickness of the shell. Such helmet shows even further improved durability as well as improved anti-ballistic properties in particular at locations remote from the rim.

[0036] Preferably, the part of the reinforcing rim that overlaps with the lateral side of the shell of the helmet has a thickness small enough not to cause an unnecessary increase in the thickness of the bottom of the helmet. It is preferred that the increase in the thickness of the helmet at its bottom is less than 30%, more preferably less than 20%, most preferably less than 10%. Such a helmet shows good anti-ballistic properties while being lightweight. Also it has an increased versatility.

[0037] The skilled person knows how to select suitable production processes for the preparation of the parts of the helmet and the helmet itself. The shell of the helmet may be produced by a process containing the steps of forming a stack of sheets containing cross plied mono-layers of unidirectional aligned UHMwPE fibers and preferably a binder, placing the stack in a mould and closing the mould to form and consolidate the stack of layers into a shell of a helmet shape. Such a process is described in WO2007/107359.

[0038] The reinforcing profile may be a machined or molded light weight metal part. Preferably however the reinforcing profile is a carbon fiber composite that is laminated along the rim of the helmet.

[0039] Preferably the sum of the weight of the shell and the reinforcing profile of the helmet according to the invention is at most 1.2 kg, more preferably at most 1.1 kg, even more preferably at most 1.0 kg.

[0040] The invention is further illustrated in the example and comparative experiments.

[0041] The helmets produced in the comparative experiments and in the example were subjected to two types of tests. The first test was a shooting test with 17 grain fragment simulating projectiles (FSP). The second test was a so called durability test.

Shooting Test

[0042] The shooting test was performed by clamping the helmet in a suitable clamping device in front of a gun. The clamping device was made in such a way that the helmet could be rotated and subsequently fixed rigidly again. In this way, the helmet was rotated after each shot and fixated again so that about eight shots could be fired at each helmet. The projectiles are 17 grain Fragment Simulating Projectiles (FSP).

[0043] The first shot is fired at an anticipated speed at which it is expected that 50% chance of perforation was present, so at an expected so-called V_{50} value. The speed of all projectiles was measured at a short distance before impact. Measurement was performed with an optical device. If a perforation occurred, the next FSP was fired at a speed that was anticipated to be 10% lower than that of the previous projectile. Again the speed was measured at short distance before impact. If a projectile was stopped without perforation, the next projectile was fired at an anticipated speed being 10% larger than the previous projectile. It is always assured that the distance between the impact locations is sufficiently large to prevent overlap of the trauma areas (impact affected areas). In general about eight shots were possible this way for each helmet. The experimental V_{50} value was obtained from the average speeds of the three highest speeds at which a stop occurred and the three lowest speeds at which a perforation occurred. In case only two stops or only two perforations are obtained, V_{50} is obtained from the two highest stops and two lowest perforations. The intrinsic kinetic energy U is obtained as the kinetic energy of an FSP at V_{50}, so $0.5\,m V_{50}^2$. The mass m of a 17 grain FSP is equal to m=0.0011 kg. The performance of a helmet is related to the intrinsic kinetic energy U at V_{50} and to the helmet mass M. Therefore a performance parameter P is derived as P=U/M.

Durability Test

[0044] The helmet is subjected to a compressive force on **2** opposing positions at its rim, at the position of the ears of a wearer. The places where the compressive force acts are chosen to be just above the reinforcing rim, therefore preventing compressing the reinforcing rim as well. The change of the shape of the helmet as a function of the compressive force is measured.

[0045] The displacement caused in the shell of the helmet at a force of 1500 N (about twice the bodyweight of a human) is considered a representative quality parameter and hereafter is referred to as ‘displacement’.

[0046] After unloading the compressive force and 5 minutes recovery, the change of the shape of the helmet is measured again. This value is referred to as ‘deformation’.

[0047] It should be noted that the force at which delamination of the helmet shell, or plasticity occurs should be well above this force of 1500 N.

[0048] In case the deformation at 1500 N is sufficiently small, this load is repeated 24 times and the displacement evolution is recorded: this is referred to as 'damage tolerance' or simply as 'durability'.

Other Test Methods

[0049] Side chains: the number of side chains in a UHPE 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 in e.g. EP 0269151);

[0050] IV: the Intrinsic Viscosity is determined according to method PTC-179 (Hercules Inc. Rev. Apr. 29, 1982) at 135° C. in decaline, 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

[0051] Tensile strength (or strength) is defined and determined on multifilament yarns as specified in ASTM D885M, using a nominal gauge length of the fibre of 500 mm, a crosshead speed of 50%/min and Instron 2714 clamps, of type Fibre Grip D5618C. For calculation of the strength, the tensile forces measured are divided by the titre, as determined by weighing 10 meters of fibre; values in GPa are calculated assuming a density of UHMwPE of 0.97 g/cm^3.

Comparative Experiment A.

[0052] A helmet was produced from a stack of 50 layers of cross plied sheet comprising two monolayers of with 80 w % unidirectional aligned UHMwPE fibers having a tensile strength of 3.5 GPa and a thermoplastic binder. The fibre orientations of the two monolayers in a cross plied sheet are about perpendicular. The helmet was produced by putting the stack in an open mould with the shape of a helmet, followed by closing the mould at a temperature of 130° C. and after consolidation at a pressure of 8 MPa (i.e. pressing force divided by projected helmet surface) during one hour, the helmet was cooled, demolded and trimmed to the desired size. The average helmet mass M was 0.876 kg. The helmet was tested and the test results are given in Table 1.

[0053] Comparative Experiment B.

[0054] A helmet was produced from a stack of 42 instead of 50 layers of Comparative Experiment A while using the same process. The pressure during moulding was similar to that of Comparative Experiment A. After demoulding and trimming, the average mass was 0.737 kg. Subsequently, after demoulding and trimming, the helmet was subjected to a laminating process with a fabric of carbon fiber. Four layers of twill weave carbon fibre fabric with an aerial density of 0.12 kg/m2 were laminated at the outside of the helmet, using a standard commercial epoxy resin. The resin could be cured at room temperature. Nevertheless, a post curing in an oven at 40° C. was performed after 2 days of curing in ambient air. Post curing was performed to ensure optimal hardening of the epoxy at all locations of the helmet. Thus a helmet was made with a hard outer skin of carbon epoxy composite. The thickness of the helmet was similar to that of the helmet of reference example 1. However, the average mass of the helmets after adding the hard outer skin was 0.946 kg. The helmet was tested and the test results are given in Table 1.

Example According to the Invention.

[0055] Helmets were produced in the same way as described in comparative experiment A. However, after demoulding and trimming, a carbon fiber epoxy composite layer was laminated around the rim of the helmet and cured in the same way as described for comparative experiment B. The carbon fiber epoxy [amount of expoxy was 40% by volume.] composite layer consists of a tape fabric with a width of 80 mm and three fibre orientations as shown in FIG. **1**. (**3**). Areal density of the tape fabric was 600 g/m^2. One fibre orientation is in the length direction of the tape. The two other fibre orientations are at +45 degrees and −45 degrees with the tape direction. Only one tape was laminated along the rim of the helmet as illustrated in the drawings with tape begin and end overlapping each other for 3 cm. The mass of the helmet with the rim was 0.940 kg. The helmet was tested and the test results are given in Table 1.

TABLE 1

Property	Comp. exp. A.	Comp. exp. B.	Example according to the invention
V_{50} [m/sec]	683	633	687
U [J]	256	220	259
P [J/kg]	293	233	276
Displacement at 1500 N, [mm]	>150 (1)	32	8 (2)
Deformation, after unloading and recovery [mm]	145	12	0.5
Damage tolerance, after 24 cycles of 1500 N [mm]	Not performed because load can not be reached	Failure (excessive deformation after 12 cycles)	6

(1) test stopped at a force of 600 N in view of excessive deformation

(2) a force of 4000 N could be reached with 35 mm displacement

[0056] The result shows that a helmet made entirely from UHMwPE monolayers shows a good helmet performance parameter P against impact of FSP. However, the durability is low. Only a low transverse compressive load can be sustained, and the resulting deformation is large. Addition of a hard outer layer improves the shell deformation, however its durability is still sub optimal. Displacements are large and only partial recovery occurs. Moreover, antiballistic performance, as expressed by the parameter P decreases considerably.

[0057] The helmet according to the invention however, shows excellent durability combined with limited displacement and almost no deformation. It is also surprisingly shows an increase in V_{50} and therefore having improved anti-ballistic properties when compared to known helmets.

1. An anti-ballistic helmet having a shell containing monolayers of uni-directional ultrahigh molecular weight polyethylene (UHMwPW) fibers, characterized that at its rim the shell is connected to a reinforcing profile.

2. A helmet according to claim **1**, wherein the shell further comprises a binder.

3. A helmet according to claim **1**, wherein the reinforcing profile is U-shaped.

4. A helmet according to claim **1**, wherein the profile is made from a metal.

5. A helmet according to claim **1**, wherein the reinforcing profile exists of composite containing fibers, and a second binder.

6. A helmet according to claim **5**, wherein the reinforcing profile contains ceramic fibers, glass fibers, basalt or silicon carbide fibers.

7. A helmet according to claim **6**, wherein the reinforcing profile contains carbon fibers

8. A helmet according to claim **5**, wherein the reinforcing profile has at least two fiber orientations.

9. A helmet according to claim **5**, wherein the U-ring has at least three fiber orientations.

10. A helmet according to claim **9**, wherein one fiber orientation is in the profile direction and two other orientations are at +45 degree and −45 degree with the profile direction.

11. A helmet according to claim **1**, wherein the sum of the weight of the shell and the reinforcing profile is at most 1.2 kg.

12. A helmet according to claim **1**, wherein the reinforcing profile has a compressive yield stress of at least 2 times the compressive yield stress of the shell as measured by ASTM D 6641.

13. A helmet according to claim **1**, wherein the part of the reinforcing rim that overlaps with the lateral side of the shell of the helmet has a length of preferably at least 0.5 times the thickness of the shell.

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