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(54) **CORRUGATED BALLISTIC ARMOR**

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(57) **ABSTRACT**

Fibrous composites comprising corrugated elements having improved resistance to penetration by ballistic projectiles/threats. The composites of the invention are useful in vehicle and aircraft armor, breastplates, hand-held shields, helmets, architectural shields, explosion containment, explosion management and other applications.

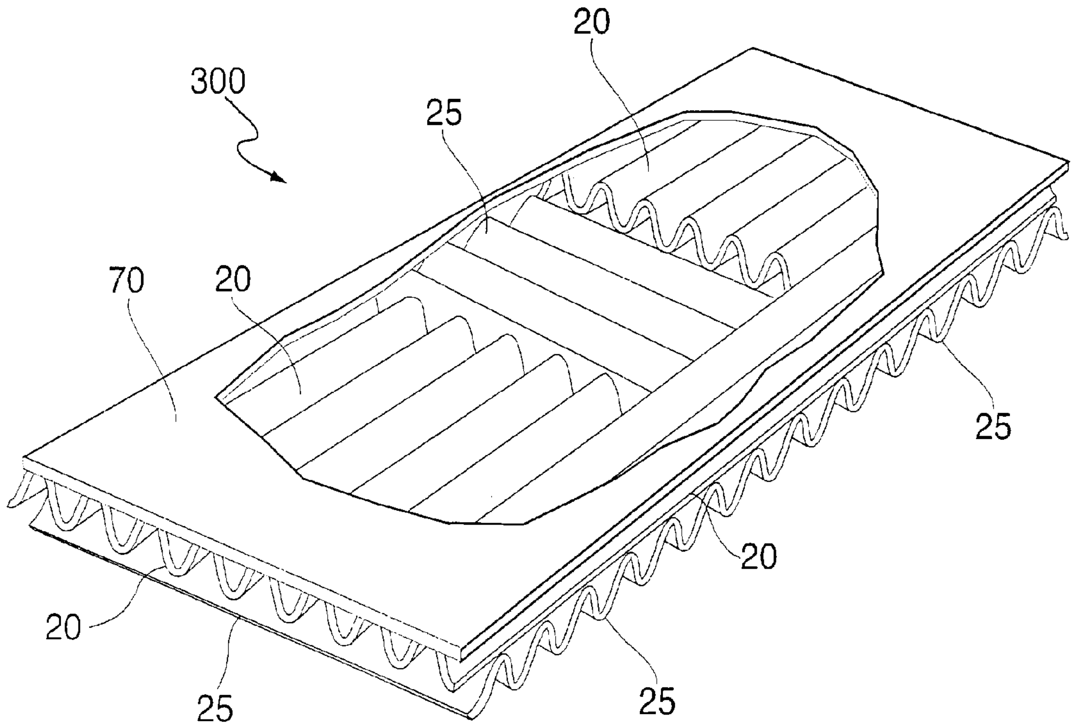
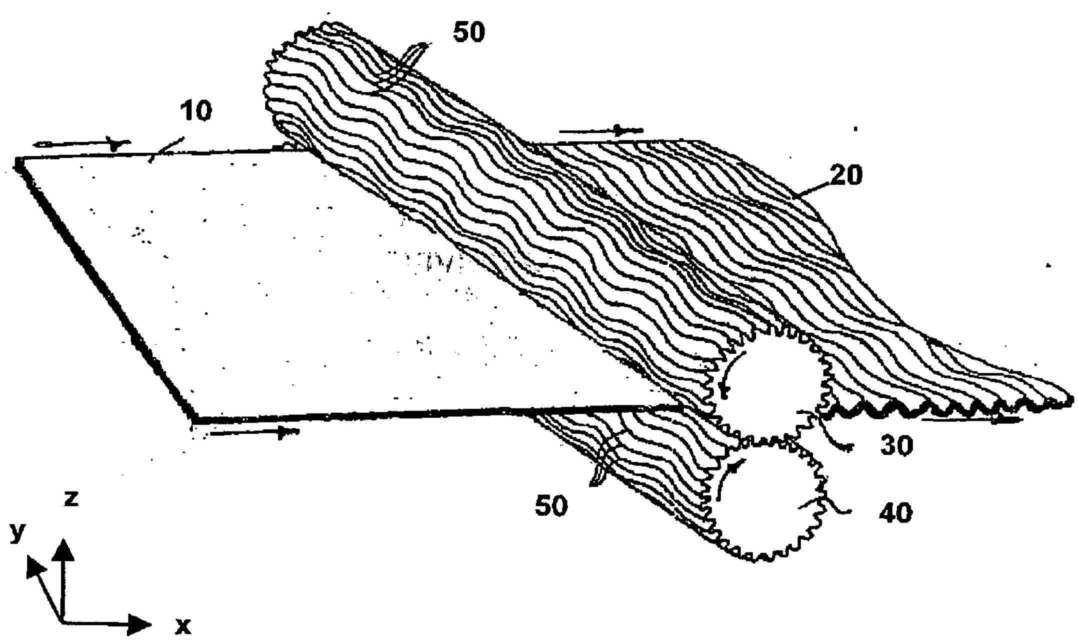


FIGURE 1



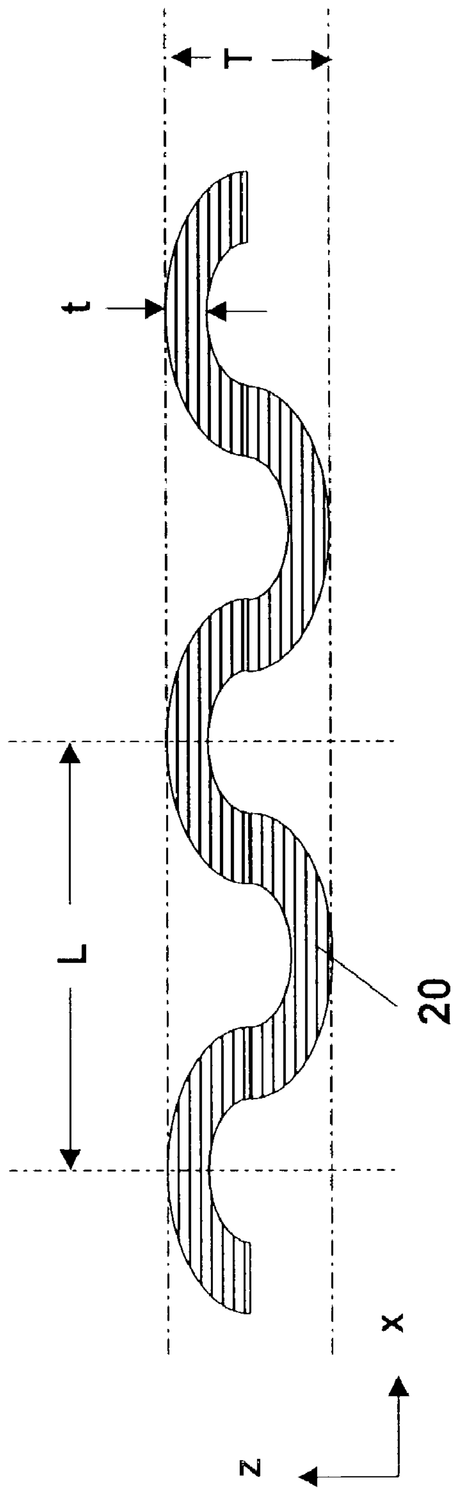


FIGURE 2

FIGURE 3

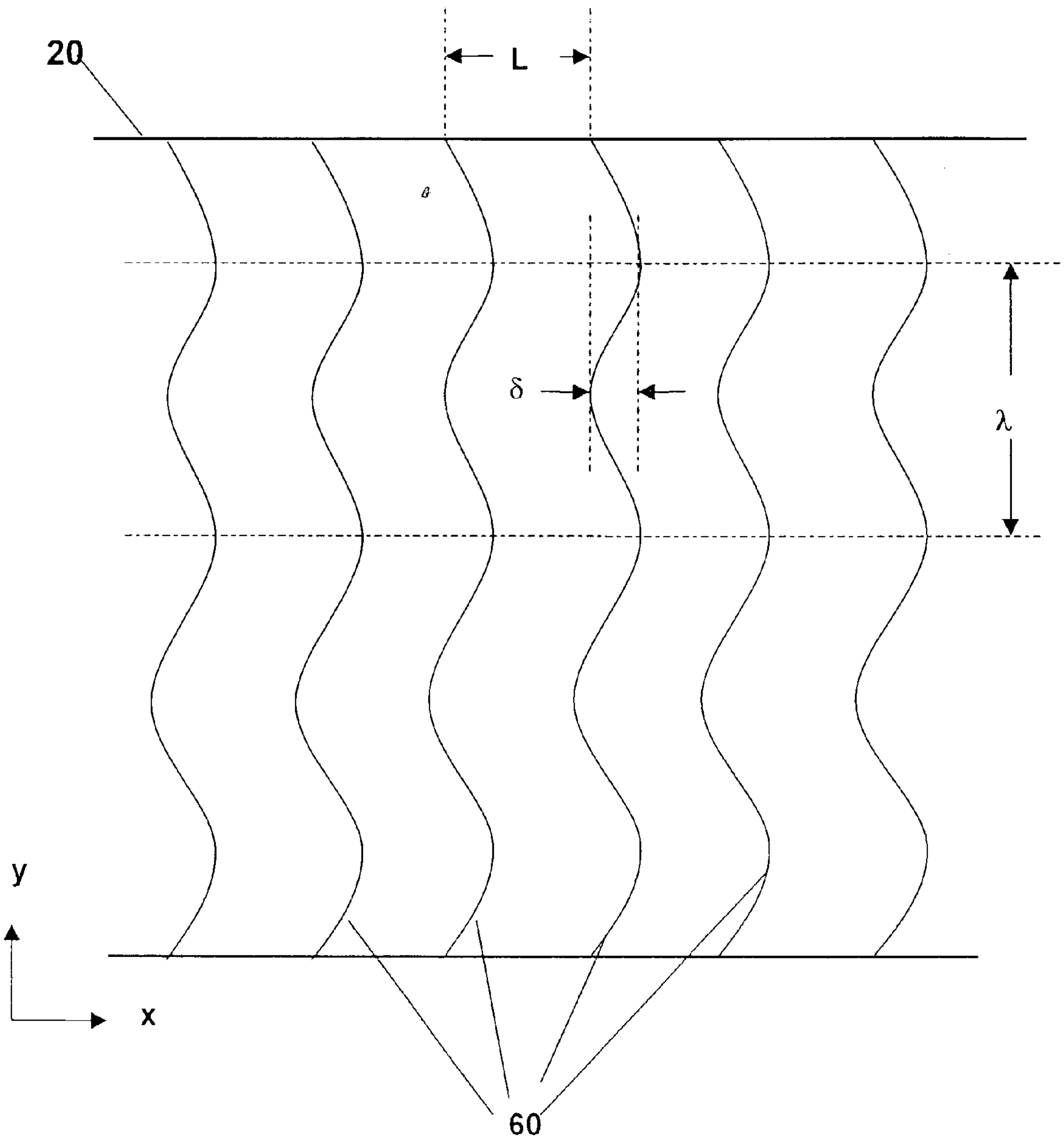


FIGURE 4

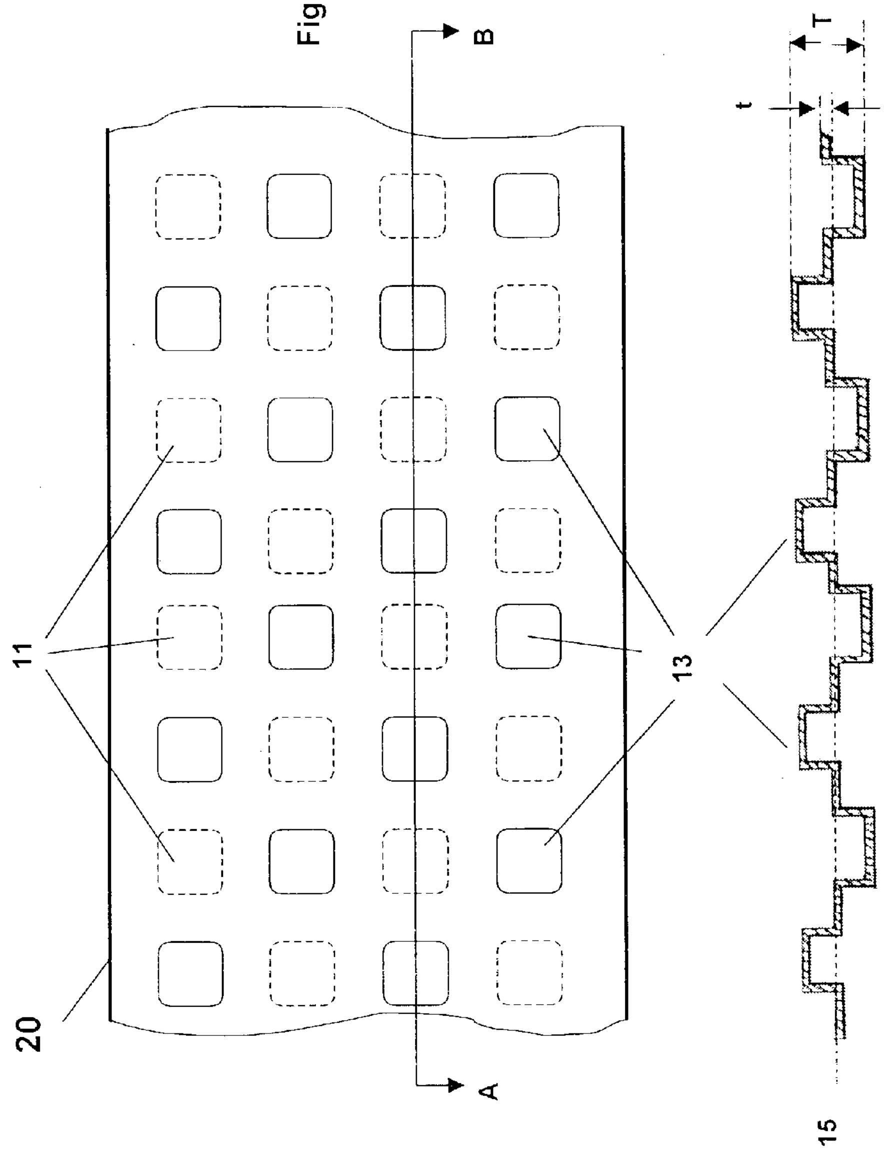


Fig. 4a

Fig. 4b
Section AB

FIGURE 5

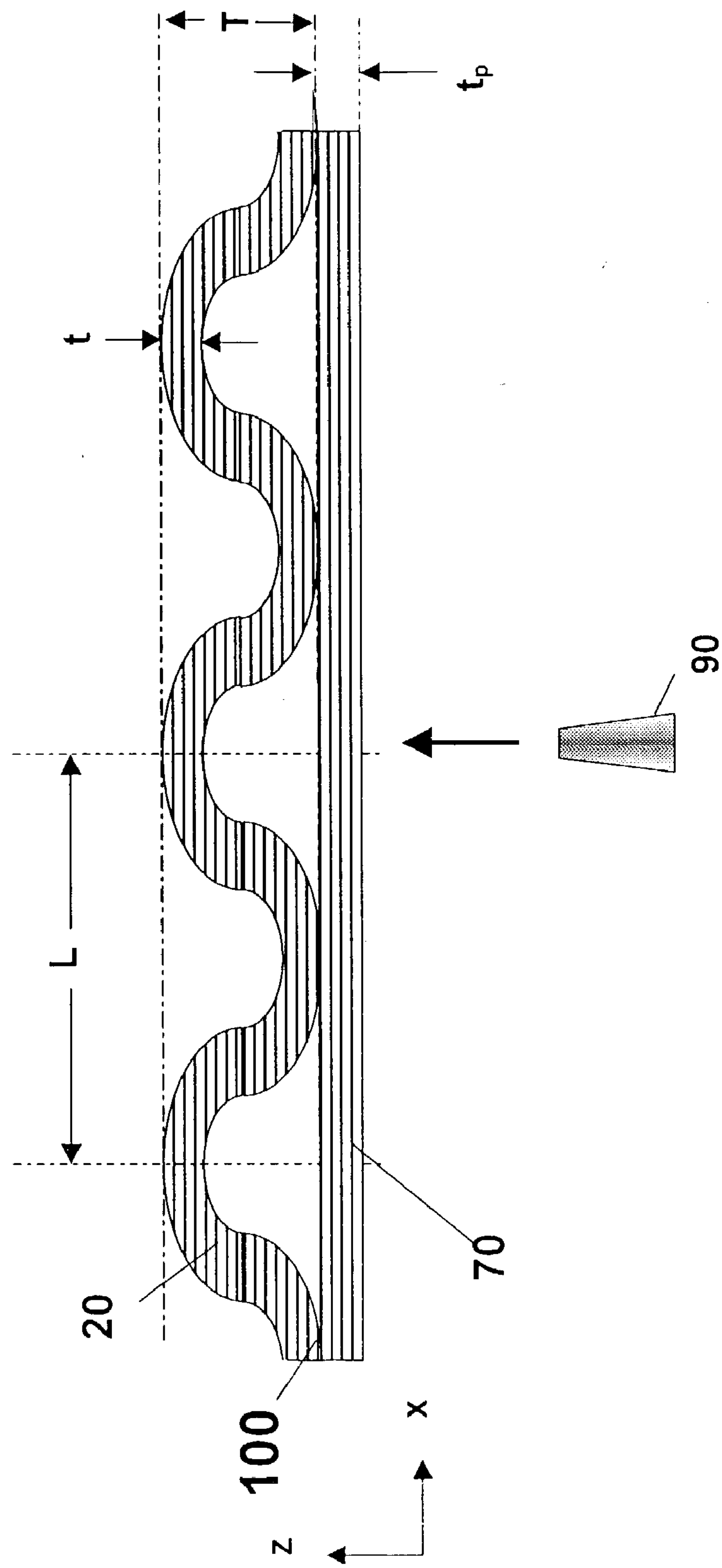
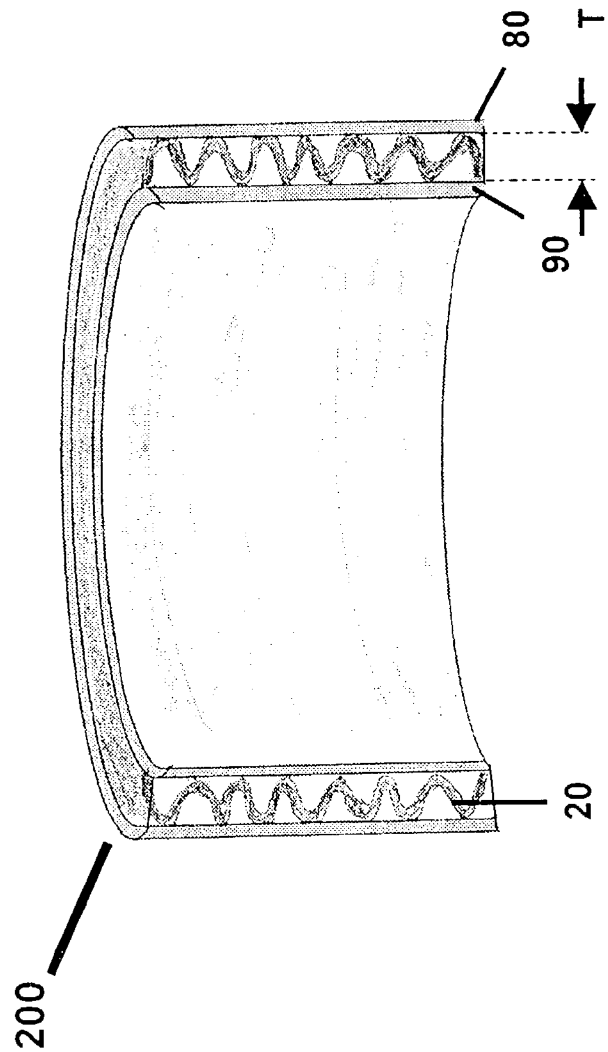


FIGURE 6



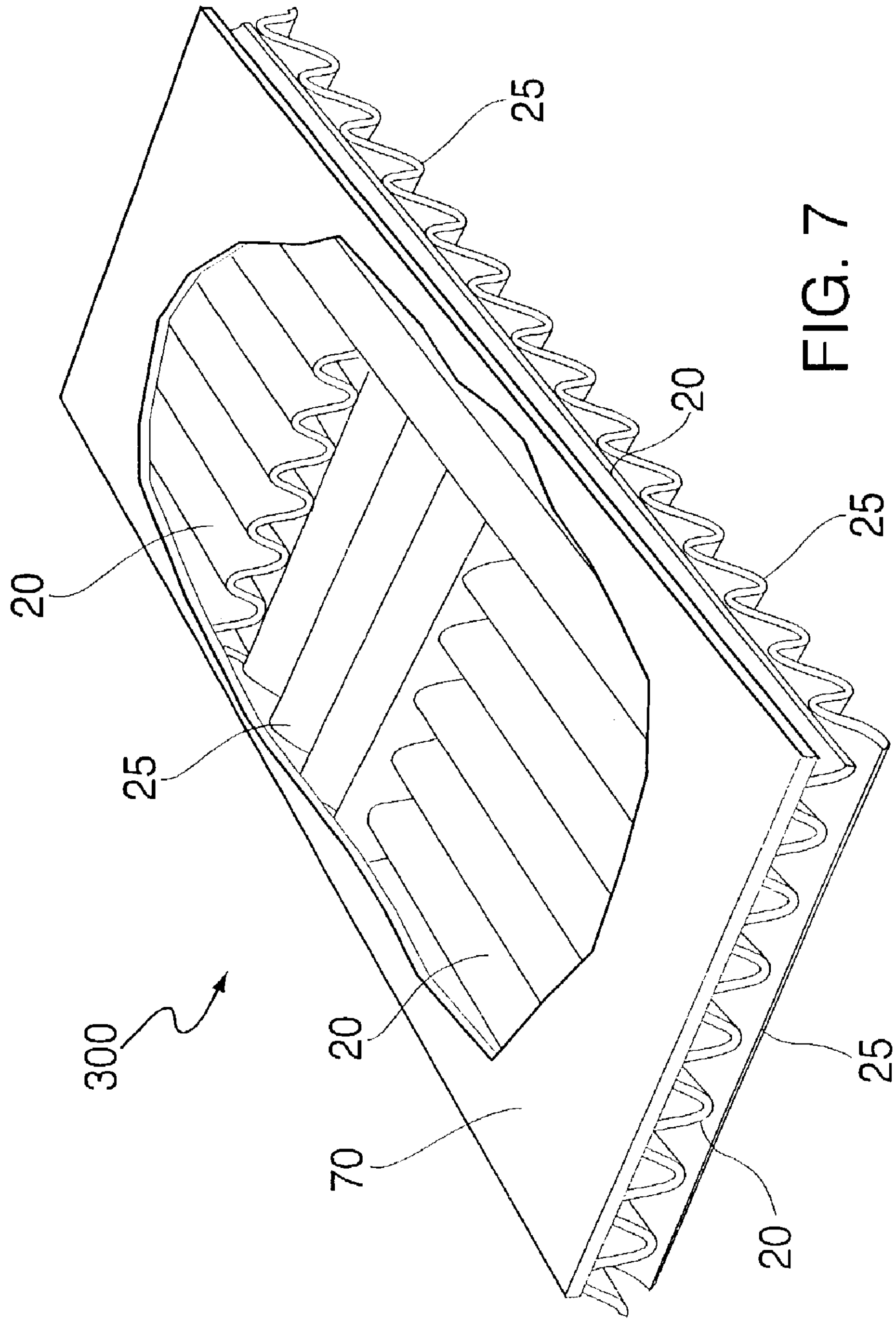
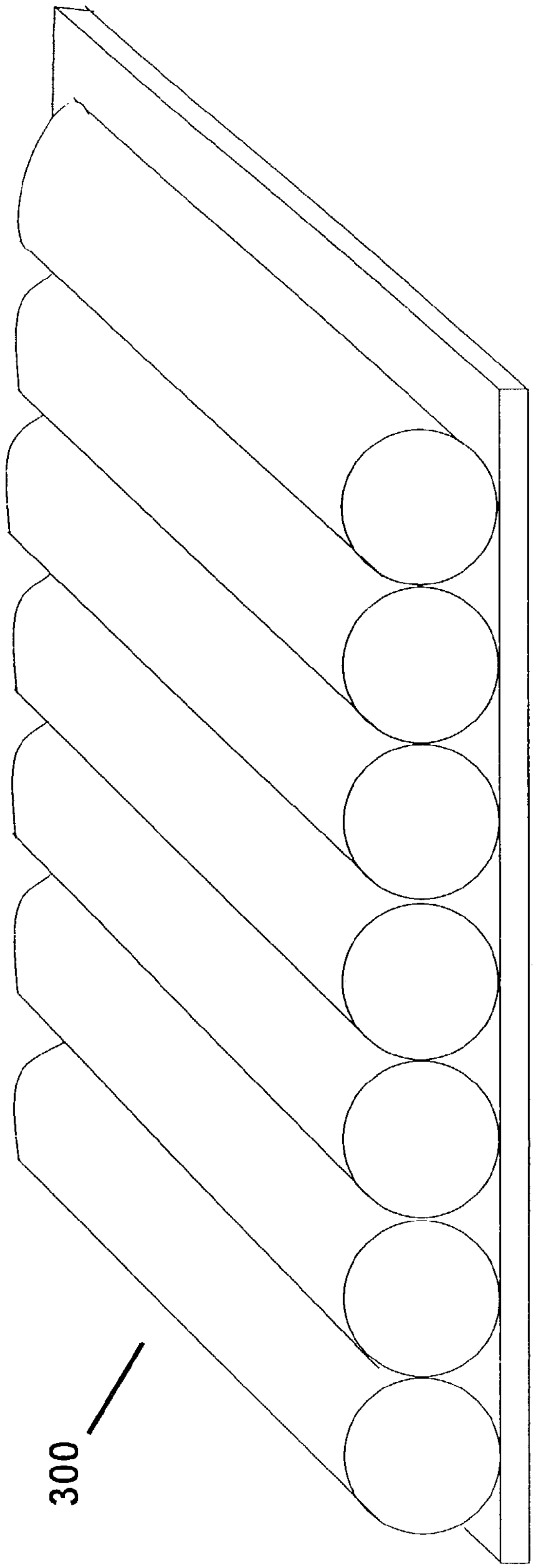


FIG. 7

FIGURE 8



CORRUGATED BALLISTIC ARMOR

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] This invention relates to ballistic armor. More particularly, the invention relates to fibrous composites comprising corrugated elements and having improved resistance to penetration by ballistic projectiles and explosions. The composites of the invention are useful in vehicle and aircraft armor, breastplates, hand-held shields, helmets, architectural shields, explosion containment, explosion management and other applications.

[0003] 2. Description of the Related Art

[0004] Fiber-based composites for ballistic-resistant articles such as panels, helmets and vests have been in use for several decades. Such composites display varying degrees of resistance to penetration by ballistic impact from projectiles such as bullets and shrapnel and the like. Descriptions of ballistic-resistant composites which include high strength fibers made from materials such as polyethylene, aramids and polybenzazoles are found for example, in U.S. Pat. Nos. 6,268,301 B1; 6,248,676 B1; 6,219,842 B1; 5,677,029; 5,587,230; 5,552,208; 5,330,820; 5,196,252; 5,190,802; 5,187,023; 5,185,195; 5,175,040; 5,167,876; 5,165,989; 5,149,391; 5,124,195; 5,112,667; 5,061,545; 5,006,390; 4,953,234; 4,916,000; 4,883,700; 4,820,568; 4,748,064; 4,737,402; 4,737,401; 4,681,792; 4,650,710; 4,623,574; 4,613,535; 4,584,347; 4,563,392; 4,543,286; 4,501,856; 4,457,985; and 4,403,012; PCT Publication No. WO 91/12136; and a 1984 publication of E.I. du Pont De Nemours International S.A. entitled "Lightweight Composite Hard Armor Non Apparel Systems with T-963 3300 dtex DuPont Kevlar 29 Fibre."

[0005] Ballistic armor including corrugated components has been described in U.S. Pat. Nos. 6,357,332 B1 and 5,149,910. U.S. Pat. No. 6,357,332 B1 describes metallic/intermetallic composite laminates. U.S. Pat. No. 5,149,910 describes an armor with a corrugated metal spoiler plate in front of alumina tiles and an aluminum anvil.

[0006] Corrugated composite materials of many types have been well known for many other purposes. A corrugated blanket comprising high strength, low modulus of elasticity filaments is described in U.S. Pat. No. 3,974,313 for use in capturing parts escaping from a bursting machine, such as a jet engine. U.S. Pat. No. 4,568,593 describes a corrugated composite panel consisting of a center ply of longitudinal unidirectional filaments and upper and lower transverse layers with unidirectional filaments oriented perpendicular to the longitudinal filaments. U.S. Pat. No. 4,946,721 describes a corrugated composite for the absorption of energy where a pressure is applied parallel to the width of the corrugations. U.S. Pat. No. 3,917,030 describes stress-limiting devices, including corrugated members. Additionally, corrugated cardboard containers have been in use since at least the early years of the 20^{th} century. EP 0 424 526 A1 describes some factors related to bending and shearing rigidity in corrugated composite bodies.

[0007] Each of these references represents an advance in the state of its respective art; however none suggests the constructions of the composites of this invention, and none satisfies all of the needs met by this invention.

[0008] In many applications where ballistic resistance is required, such as in military aircraft, helicopters, body armor and hand-held shields, there are severe limitations on weight. It is imperative in such applications that armor materials have the highest possible ballistic effectiveness per unit of weight. A need exists for materials that provide enhanced weight efficiency of ballistic resistance.

SUMMARY OF THE INVENTION

[0009] This invention relates to corrugated fibrous composites having superior weight efficiency of resistance to penetration by ballistic projectiles. In one embodiment, the invention is a ballistic-resistant article of manufacture comprising a plurality of corrugations. The corrugated article comprises a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix, wherein the effective thickness T of the ballistic-resistant article, in proportion to the thickness dimension of the plurality of layers of fibrous networks t, is from about 1.2 to about 10.

[0010] In another embodiment, the invention is a ballistic-resistant article of manufacture comprising: an element comprising a plurality of corrugations, a front face, a rear face, and a panel attached to at least one of the faces. The corrugated element comprises a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix, wherein the effective thickness of the corrugated element, in proportion to the thickness dimension of said plurality of layers of fibrous networks, is from about 1.2 to about 10.

[0011] In yet another embodiment the invention is a ballistic-resistant article of manufacture comprising a front face, a rear face and a plurality of plies. Each of the plies comprises a plurality of corrugations and a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix, wherein the effective thickness of each corrugated ply, in proportion to the thickness dimension of its respective plurality of layers, is from about 1.2 to about 10, and wherein the direction of the corrugations in one ply is rotated with respect to the direction of the corrugations in another ply.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] In the accompanying drawing figures:

[0013] **FIG. 1** illustrates one method of producing a corrugated ballistic-resistant article of the invention from a ballistic-resistant flat panel of the prior art.

[0014] **FIG. 2** is a sectional view of a corrugated ballistic-resistant article of the invention along a z-x plane as defined in **FIG. 1**.

[0015] **FIG. 3** is a plan view of a corrugated ballistic-resistant article of the invention along an x-y plane tangent to the crests of the corrugations.

[0016] **FIG. 4*a*** is a plan view of a corrugated ballistic-resistant article of the invention wherein the corrugations are dimples and mounds in a neutral surface.

[0017] **FIG. 4*b*** is a sectional view along the A-B plane of **FIG. 4*a***.

[0018] **FIG. 5** is a sectional view of a ballistic-resistant article of the invention wherein a panel is bonded to one of the faces of the corrugated element.

[0019] **FIG. 6** is a sectional view of a ballistic-resistant article of the invention with cylindrical curvature wherein face panels are bonded to each of the faces of the corrugated element.

[0020] **FIG. 7** is a cutaway drawing illustrating a three-ply ballistic-resistant article of the invention comprising a flat outer panel and two corrugated plies with the directions of the corrugations in the adjacent plies arranged at right angles to one another.

[0021] **FIG. 8** illustrates a molding die-half suitable for the molding of corrugated panels.

DETAILED DESCRIPTION OF THE INVENTION

[0022] The invention comprises corrugated fibrous composites having superior weight efficiency of resistance to penetration by ballistic projectiles. In one embodiment, the invention is a corrugated ballistic-resistant article of manufacture, i.e., having a plurality of corrugations. The ballistic-resistant article comprises a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix, wherein the effective thickness T of the ballistic-resistant article, in proportion to the thickness dimension t of said plurality of layers of fibrous networks, is from about 1.2 to about 10.

[0023] It will be understood that a high strength, high tensile modulus fibrous network is a network comprising high strength, high modulus fibers. A high strength, high modulus fiber has a tenacity of at least about 17 g/d and a modulus of elasticity (tensile modulus) of at least about 300 g/d as measured by ASTM D2256 at 10 inch (25.4 cm) gauge length and a strain rate of 100%/min.

[0024] The ballistic-resistant articles of the invention include essentially planar forms having no out-of-plane curvature, as well as forms having out-of-plane curvature. The out-of-plane curvature may be cylindrical, saddle-shaped or of any complex shape, particularly including a form shaped to the surface of a human body.

[0025] An essentially planar corrugated composite of the invention may be produced by corrugating a flat panel comprising layers of high strength, high tensile modulus fibrous networks in a matrix, as illustrated in **FIG. 1**. A flat panel **10** comprising a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix is pressed at elevated pressure and temperature between matched corrugated rollers **30**. The corrugated rollers are provided with vertically extending ridges **40**, **50** and grooves that are impressed into the flat panel **10** to produce a corrugated article of the invention **20**. This method is useful for continuous production of essentially planar corrugated articles of indefinite length.

[0026] Alternatively, a corrugated composite panel of limited dimensions may be formed by pressing a flat panel at sufficient time, temperature and pressure between stationary matched dies having the desired corrugations. Molding between stationary matched dies is particularly useful for molding corrugated composites of the invention having non-planar forms such as might be used in personnel shields and having complex curvatures such as might be used for woman's body armor.

[0027] A flat composite panel suitable for forming into a ballistic resistant corrugated article of the invention may be formed for example by the prior art methods cited above and particularly by the methods of U.S. Pat. Nos. 4,916,000; 5,552,208; 5,149,391; 5,173,138, and 5,766,725, the disclosures of which are hereby specifically incorporated by reference to the extent not incompatible herewith.

[0028] **FIG. 2** illustrates a cross-section of an essentially planar corrugated article **20** of the invention in the z-x plane of **FIG. 1**. The thickness dimension of the plurality of layers of fibrous networks is t. Preferably, the thickness t is constant throughout the article. The effective thickness T of the corrugated article is defined as the distance between planes tangent to the opposite surfaces of two adjacent corrugations. Preferably, the effective thickness T is constant throughout the article. The corrugated articles of the invention possess a T/t ratio of from about 1.2 to about 10, preferably from about 1.5 to about 5. The spacing between the crests of the corrugations in the z-x plane is L. The crest-to-crest spacing, in proportion to the thickness dimension of the plurality of layers of fibrous networks, L/t, is from about 2 to about 30. Preferably, L/t is from about 4 to about 20.

[0029] The thickness dimension t of the plurality of layers of fibrous networks will depend on the ballistic threat that it is desired to defeat, the nature of the fibers and matrix, and the geometry of the fibrous networks. The man of ordinary skill in the art will know how to select fibers, matrix and fiber network geometry for a flat panel to defeat this threat. With the above selections of T/t and L/t ratios, the corrugated article of the invention will permit the use of fewer and therefore less massive fibrous layers to defeat the same ballistic threat. For example, a corrugated ballistic-resistant article of the invention, when tested by MIL-STD 662E dated 22 Jan. 1987 with a 9 mm 124 grain FMJ bullet, shows at least 10% greater specific energy absorption (J-m^2/kg) at the V50 velocity than a flat plate having the same layers of the same fibrous networks in the same matrix.

[0030] **FIG. 3** is a plan view of an essentially planar corrugated article of the invention **20**. The wavy lines **60** represent the trace of the crests of the corrugations upon a plane tangent to the surface of the article. In general, the corrugations meander in the x-y plane with a periodicity λ in the y direction and amplitude δ in the x direction. Preferably λ and δ are constant throughout the article. Preferably, the meandering ratio δ/λ is from zero (corrugation crests follow a straight line) to about 1. Preferably δ/L is from zero to about 0.9.

[0031] It is preferred that the corrugations are approximately sinusoidal in z-x and x-y cross-sections. However, the corrugations may have other shapes, such as rectangular, triangular or other forms without departing from the invention. **FIG. 4*a*** is a plan view of a corrugated article of the invention **20** wherein the corrugations take the form of isolated, essentially rectangular dimples **11** and mounds **13** in a neutral plane **15**. **FIG. 4*b*** is a sectional view along A-B of this arrangement. These corrugated articles of the invention **20** also possess a T/t ratio from about 1.2 to about 10, preferably from about 1.5 to about 5.

[0032] In another embodiment, the invention is a ballistic-resistant article of manufacture comprising: an element having a plurality of corrugations, a front face, a rear face and a panel attached to at least one of the faces. The corrugated element comprises a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix, wherein the effective thickness of said corrugated element, in proportion to the thickness dimension of said plurality of layers of fibrous networks, is from about 1.2 to about 10. **FIG. 5** is a cross-section **100** of an essentially planar form of this embodiment of the invention. **FIG. 6** illustrates a non-planar form of this embodiment having out-of-plane cylindrical curvature **200**.

[**0033**] In **FIG. 5**, a panel **70** is attached to a corrugated element **20** comprising a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix. The panel is attached to the corrugated element on at least the side facing a ballistic projectile **90**. The corrugated element **20** possesses a T/t ratio, as previously defined, from about 1.2 to about 10, preferably from about 1.5 to about 5. The crest-to-crest spacing, in proportion to the thickness dimension of the plurality of layers of fibrous networks, L/t as previously defined, is from about 2 to about 30, more preferably from about 4 to about 20.

[**0034**] In general, the corrugations meander in the x-y plane with a periodicity λ in the y direction and an amplitude δ in the X direction. Preferably λ and δ are constant throughout the article. Preferably, the meandering ratio δ/λ ranges from zero (corrugation crests follow a straight line) to about 1. Preferably δ/L is from zero to about 0.9.

[**0035**] Panel **70** preferably has a thickness t_p ranging from about ½t to about 2t. It is also preferred that the material forming panel **70** is selected from the group consisting of a ceramic, a metal and a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix. Panel **70** is preferably attached to the corrugated element by an adhesive, and more preferably, the points of attachment are spaced no closer than alternate corrugations.

[**0036**] In **FIG. 6**, the illustrated article has an element **20** comprising a corrugated sheet and panels **80** and **90** attached to the faces of the corrugated element. The corrugated core element and the face panels have been molded to have cylindrical curvature about a vertical axis. The corrugated element **20** possesses a T/t ratio, as previously defined, ranging from about 1.2 to about 10, preferably from about 1.5 to about 5. The crest-to-crest spacing, in proportion to the thickness dimension of the plurality of layers of fibrous networks, L/t as previously defined, ranges from about 2 to about 30, preferably from about 4 to about 20. In general, the corrugations meander with a periodicity λ and an amplitude δ. Preferably λ and δ are constant throughout the article. It is also preferred that the meandering ratio δ/λ ranges from zero (corrugation crests follow a straight line) to about 1, and that δ/L is from zero to about 0.9.

[**0037**] Panels **80** and **90** preferably have a thickness ranging from about ½t to about 2t. The preferred material for panels **80** and **90** are selected from the group consisting of a ceramic, a metal, a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix, and combinations thereof. The panels are preferably attached to the corrugated element by an adhesive, with the points of attachment preferably spaced no closer than alternate corrugations per face.

[**0038**] Articles of the invention having out-of plane curvature are useful for personnel shields and body armor, among other applications. Molding to conform to the surface of the human body is particularly advantageous.

[**0039**] In yet another embodiment, the invention is a ballistic-resistant article of manufacture comprising: a plurality of corrugated plies, wherein each ply is comprised of a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix, and wherein the effective thickness of each said corrugated ply, in proportion to the thickness dimension of said plurality of layers comprising each said corrugated ply, ranges from about 1.2 to about 10, and wherein the direction of the corrugations in one ply is rotated with respect to the direction of the corrugations in another ply. Preferably, a flat panel is attached to one of the outer corrugated plies.

[**0040**] **FIG. 7** is a cutaway drawing illustrating a three-ply, ballistic-resistant article **200** of the invention consisting of an outer panel **70** and two corrugated plies **20**, **25** with the directions of the corrugations in the adjacent plies arranged at right angles to one another. It will be understood that more than three plies may be used and that the angle between the directions of the corrugations may be 30°, 45°, 60° or other convenient angle.

[**0041**] A panel is preferably attached to the corrugated plies on at least the side facing a ballistic projectile or threat. The corrugated plies **20**, **25** each possesses a T/t ratio, as previously defined, of from about 1.2 to about 10. The T/t ratio is preferably the same for each ply and ranges from about 1.5 to about 5. The crest-to-crest spacing in each ply, in proportion to the thickness dimension of the plurality of layers of fibrous networks, L/t as previously defined, is from about 2 to about 30. Preferably, the L/t ratio is the same for each ply and ranges from about 4 to about 20.

[**0042**] In general, the corrugations in each ply meander in the x-y plane with a periodicity λ in the y direction and an amplitude δ in the x direction. Preferably λ and δ are constant throughout the article. It is also preferred that the meandering ratio δ/λ ranges from zero (corrugation crests follow a straight line) to about 1, and that δ/L is from zero to about 0.9.

[**0043**] The panel preferably has a thickness t_p of from about ½t to about 2t. It is preferred that material of the panel is selected from the group consisting of a ceramic, a metal, and a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix. The panel is preferably attached by an adhesive with its points of attachment to the adjacent corrugated element being spaced no closer than alternate corrugations.

[**0044**] In each of the above embodiments, it is preferred that the layers of fibrous networks are comprised of sheet-like arrays of fibers in which the fibers are aligned substantially parallel to one another along a common fiber direction. It is further preferred that the fiber alignment directions in selected layers are rotated with respect to the fiber alignment of another layer. It is most preferred that the fibers in a given layer are rotated perpendicular to the fibers in adjacent layers.

[**0045**] In each of the above embodiments, it is preferred that a majority of the layers is comprised of fibers having a tenacity of at least about 17 g/d, a modulus of elasticity (tensile modulus) of at least about 300 g/d and an energy-to-break of at least about 20 J/g as measured by ASTM D2256 at 10 inch (25.4 cm) gauge length and a strain rate of 100%/min. More preferably, a majority of the layers is comprised of fibers having a tenacity of at least about 30 g/d, a modulus of elasticity of at least about 800 g/d and energy-to-break at least about 40 J/g.

[**0046**] It is further preferred that the fibers are selected from the group consisting of polyethylene fibers, aramid fibers and polybenzazole fibers. It is most preferred that the fibers are selected from the group consisting of polyethylene fibers, poly(p-phenylene terephthalamide) and poly(p-phenylene-2,6-benzobisoxazole) fibers.

[**0047**] The matrix resin in each of the above embodiments will be selected according to its end application. If the ballistic-resistant article supports a structural load in the end application, the matrix resin is preferably a rigid resin with a tensile modulus of at least about 300,000 psi (2.1 GPa) as measured by ASTM D638. Otherwise, it is preferred that the matrix resin is an elastomeric material with a tensile modulus less than about 6,000 psi (41 MPa) as measured by ASTM D638.

EXAMPLES

Comparative Example 1

[**0048**] Thirty-seven layers of SPECTRA SHIELD® PCR material were molded into flat panels of 33 cm×33 cm×5.5 mm dimensions at a temperature of 116° C. at a pressure of 500 psi (3.44 MPa) for a period of 10 minutes. The areal density (AD) of the panels was 1.00 lb/ft2 (4.89 kg/m2).

[**0049**] SPECTRA SHIELD® PCR is a product of Honeywell International Inc. consisting of two sheets of unidirectional SPECTRA® high strength, high modulus polyethylene fibers cross-plied 0°/90° with 20 wt. % of a thermoplastic elastomer resin matrix. The SPECTRA® polyethylene fibers have a tenacity of 30 g/d, a tensile modulus of 850 g/d and an energy-to-break of 45 g/d.

[**0050**] The flat panels were subjected to ballistic testing by the method of MIL-STD 662E dated 22 Jan. 1987 using a .22 caliber, 17 grain fragment simulator (FSP) and a 9 mm, 124 grain full metal jacket (FMJ) bullet to determine the corresponding V50 velocities and specific energy absorption. The V50 velocity is the velocity at which there is a 50% probability that the panel will be penetrated by the projectile. The specific energy absorption (SEAT) is the kinetic energy absorbed by the panel divided by the areal density of the panel. The SEAT is a measure of the weight efficiency of ballistic protection. The V50 velocities and SEAT's of the panels are shown in Tables I and II below.

Examples 1-3

[**0051**] 5.5 mm-thick flat panels were prepared from thirty-seven layers of SPECTRA SHIELD® PCR material as described in Comparative Example 1. The flat panels had an areal density of 1.00 lb/ft2 (4.89 kg/m2).

[**0052**] The flat panels were re-molded into corrugated panels by pressing between matched steel dies at a temperature of 116° C. and a pressure of 500 psi (3.44 MPa) for 10 minutes. The upper and lower molding dies each consisted of steel cylinders in side-by-side parallel arrangement welded to a steel back plate. A lower die-half **300** is illustrated in **FIG. 8**.

[**0053**] In Example 1, the diameter of the steel cylinders was 0.50 inch (12.7 mm) and produced a corrugation with 0.50 inch (12.7 mm) crest-to crest spacing. In Example 2 the diameter of the steel cylinders was 1.0 inch (25.4 mm) and produced a corrugation with 1.0 inch (25.4 mm) crest-to-crest spacing. In Example 3 the diameter of the steel cylinders was 2.0 inches (50.8 mm) and produced a corrugation with 2.0 inches (50.8 mm) crest-to-crest spacing. The ratio T/t between the effective thickness of the corrugated panels and the 5.5-mm thickness dimension of the 37 layers of the SPECTRA SHIELD® PCR material constituting the panels is shown in Table I.

[**0054**] The corrugated panels were subjected to ballistic testing by the method of MIL-STD 662E dated 22 Jan. 1987 using a .22 caliber, 17 grain FSP and a 9 mm, 124 grain FMJ bullet. The panels were tested with the projectile striking either the crest of a corrugation, a trough, or the sloped area about midway between a crest and a trough. The V50 velocities, specific energy absorption (SEAT) and the % increase in SEAT relative to the flat panel of Comparative Example 1 were as shown in Tables I and II below.

TABLE I

Ballistic Testing with .22 Caliber 17 gr. FSP							
Ex. Or Comp. Ex,	Corrugation Spacing, in.	T/t	AD, lb/ft2	Strike Position	V50, ft/sec	SEAT, J-m2/kg	% Increase in SEAT
Comp. 1	Flat	1.00	1.00	Flat	1705	30.4	—
1	0.5	1.25	1.02	Crest	1786	32.7	8
1	0.5	1.25	1.02	Trough	1826	34.2	13
2	1.0	1.82	1.03	Crest	1911	37.1	23
2	1.0	1.82	1.03	Slope	1925	37.7	25
2	1.0	1.82	1.03	Trough	1722	30.1	0
3	2.0	2.49	1.04	Crest	1928	37.5	24
3	2.0	2.49	1.04	Slope	1949	38.3	27
3	2.0	2.49	1.04	Trough	1750	30.9	2

[0055]

TABLE II

Ballistic Testing with 9 mm, 124 gr. FMJ Bullet							
Ex. Or Comp. Ex,	Corrugation Spacing, in.	T/t	AD, lb/ft^2	Strike Position	V50, ft/sec	SEAT, $J\text{-}m^2/kg$	% Increase in SEAT
Comp. 1	Flat	1.00	1.00	Flat	1673	212	—
1	0.5	1.25	1.02	Crest	1814	249	17
1	0.5	1.25	1.02	Trough	1847	258	22
2	1.0	1.82	1.03	Crest	1937	283	33
2	1.0	1.82	1.03	Trough	1867	263	24
3	2.0	2.49	1.04	Crest	1960	290	37

[0056] It is seen that the corrugated articles of the invention defeated the projectiles at higher velocity and with greater weight efficiency than the flat panels. It is also seen that as the T/t ratio of the corrugated panel increased the weight efficiency of ballistic effectiveness increased for projectile strikes on the corrugation crests or slopes. Moreover, the corrugated articles were generally more ballistic resistant when the projectile struck the crest or the slope of a corrugation rather than the trough.

[0057] Without being held to a particular theory of why the inventive corrugated articles were superior to the flat panels, it is believed that this resulted from an additional energy absorption mechanism in the corrugated panels. When the projectile struck the corrugations, a compressive wave was initiated in the impact area. It is believed that the corrugations were better able to bend and flatten under the impact of the projectiles than the flat panels, thus delaying and reducing the energy needed to be absorbed by ultimate tensile breakage of the high strength fibers within. The corrugations were more compliant when struck at the crest or slope rather than the trough.

Example 4

[0058] A composite article of the invention as illustrated in **FIG. 5** is prepared as follows. Two 2.7-mm thick flat panels are molded from 18 layers of SPECTRA SHIELD® PCR material as described in Comparative Example 1. The 2.7-mm thick flat panels have an areal density of 0.49 lb/ft^2 (2.39 kg/m^2).

[0059] A corrugated panel is prepared from one of the flat panels by passage at a temperature of 116° C. and a pressure of 500 psi (3.45 MPa) between corrugated rollers as shown in **FIG. 1**. The corrugated panel has a crest-to-crest spacing L of 2.0 inches (50.8 mm), a meander amplitude δ of 1 inch (25.4 mm), a meander periodicity λ of 4 inches (102 mm), an effective thickness T of 9.2 mm, a T/t ratio of 3.3, and an areal density of 0.53 lb/ft^2. The other 2.7-mm thick flat panel is bonded to a face of the corrugated panel by means of an adhesive applied to the crests of the corrugations. The final composite article of the invention consists of the flat face panel attached to the corrugated panel and has an overall thickness is of 11.9 mm and an areal density of 1.02 lb/ft^2.

[0060] Another flat panel is prepared from thirty-eight layers of SPECTRA SHIELD® PCR material. This panel is of 5.6-mm thickness and has an areal density of 1.03 lb/ft^2.

[0061] Both the composite article of the invention and the 5.6-mm flat panel are subjected to ballistic testing by the method of MIL-STD 662E dated 22 Jan. 1987 using a 9 mm caliber, 124 grain FMJ bullet. The projectile is directed at the flat panel side of the composite article of the invention as illustrated in **FIG. 5**.

[0062] It is believed that the V50 velocity and the specific energy absorption of the composite article of the invention will be superior to the flat panel having essentially the same areal density regardless of the point of impact on the composite article of the invention.

Example 5

[0063] A composite article of the invention with a flat face panel as illustrated in **FIG. 5** is prepared as described in Example 4 except that the flat panel is bonded to the corrugated panel only at the corrugation crests at the edges of the panel. The interior corrugations are left unbonded.

[0064] This composite article of the invention is believed to have higher V50 and SEAT values than the composite article of the invention described in Example 4 under assault by the same projectile.

Example 6

[0065] A composite article of the invention having cylindrical out-of-plane curvature as illustrated in **FIG. 6** is prepared as follows. Two uncorrugated panels having cylindrical curvature are each molded from 12 layers of SPECTRA SHIELD® PCR material by pressing between matched cylindrical steel dies at a temperature of 116° C. and a pressure of 500 psi (3.44 MPa) for a period of 10 minutes. A third corrugated panel having cylindrical curvature is prepared by molding 12 layers of SPECTRA SHIELD® PCR material between matched cylindrical corrugated steel dies at a temperature of 116° C. and a pressure of 500 psi (3.44 MPa) for a period of 10 minutes. The corrugated panel has a T/t ratio of 2.0. The two uncorrugated cylindrical panels are attached to each face of the corrugated cylindrical panel by means of an adhesive applied to the crests of the corrugations. The final ballistic-resistant article has a thickness of 5.4 mm and an areal density of 0.98 lbs/ft^2 (4.78 Kg/m^2).

[0066] It is believed that the V50 velocity and the specific energy absorption of the composite article of the invention will be superior to a flat panel constructed with the same materials and having essentially the same areal density.

Example 7

[0067] A composite article of the invention is prepared having complex curvature is prepared using matched molding dies as follows.

[0068] A first set of molding dies is machined to have surfaces conforming to the front surface of a woman's form. A second set of molding dies is machined to have surfaces conforming to the front surface of a woman's form but with vertically extending ridges and grooves machined alternately into the matching die surfaces.

[0069] Two panels having complex curvature are each molded from 12 layers of SPECTRA SHIELD® PCR material by pressing between the first set of matched molding dies at a temperature of 116° C. and a pressure of 500 psi (3.44 MPa) for a period of 10 minutes. A third corrugated panel having the corresponding complex curvature is prepared by molding 12 layers of SPECTRA SHIELD® PCR material between the second set of matched molding dies at a temperature of 116° C. and a pressure of 500 psi (3.44 MPa) for a period of 10 minutes. The corrugated panel has a T/t ratio of 2.5. The two uncorrugated panels are attached to each face of the corrugated panel by means of an adhesive applied to the crests of the corrugations. The final ballistic-resistant article has a thickness of 5.4 mm and an areal density of 0.98 lbs/ft^2 (4.78 Kg/m^2).

[0070] It is believed that the V50 velocity and the specific energy absorption of the composite article of the invention will be superior to a flat panel constructed with the same materials and having essentially the same areal density.

Example 8

[0071] A composite article of the invention as illustrated in **FIG. 7** is prepared as follows. Three 1.8-mm thick flat panels are molded from 12 layers of SPECTRA SHIELD® PCR material as described in Comparative Example 1. The three 1.8-mm thick flat panels each have an areal density of 0.32 lb/ft^2 (1.61 kg/m^2).

[0072] Two corrugated panels are prepared from two of the flat panels by remolding as described in Example 3. The corrugated panels have a crest-to-crest spacing of 2.0 inches (50.8 mm), an effective thickness T of 8.4 mm, a T/t ratio of 4.65 and an areal density of 0.36 lb/ft^2 (1.76 kg/m^2).

[0073] One of the corrugated panels is rotated and placed upon the other as illustrated in **FIG. 7** so that the direction of the corrugations in one panel are at right angles to the direction of the corrugations in the other panel. The corrugated panels are attached to each other by means of an adhesive applied to their points of contact.

[0074] The third 1.8-mm flat panel is attached to the face of one of the corrugated panels by means of an adhesive applied to the crests of alternate corrugations.

[0075] The final composite article of the invention, as illustrated in **FIG. 7**, consists of a face panel and two corrugated panels with the directions of their corrugations at right angles to one another. The overall thickness of this composite article is 18.6 mm and it has an areal density of 1.04 lb/ft^2 (5.08 kg/m^2).

[0076] Another flat panel is prepared from thirty-eight layers of SPECTRA SHIELD® PCR material. This panel is of 5.6-mm thickness and has an areal density of 1.03 lb/ft^2.

[0077] Both the composite article of the invention and the 5.6 mm flat panel are subjected to ballistic testing by the method of MIL-STD 662E dated 22 Jan. 1987 using a 9 mm caliber, 124 grain FMJ bullet. The projectile is directed at the flat panel side of the composite article of the invention.

[0078] It is believed that the V50 velocity and the specific energy absorption of the composite article of the invention will be superior to the flat panel having essentially the same areal density regardless of the point of impact on the composite article of the invention.

Example 9

[0079] A KEVLAR® 49 fabric (E. I DuPont Style 120) is impregnated with 20 wt. % KRATON D1107 poly(styrene-isoprene-styrene) triblock thermoplastic elastomer. The KEVLAR® fabric is a plain weave with 13×13 warp and fill yarns per centimeter. KEVLAR® 49 (poly(p-phenylene terephthalamide)) yarns have a tenacity of 28 g/d and a tensile modulus of 976 g/d.

[0080] Fifty layers of the impregnated fabric are molded into two flat panels of 33 cm×33 cm×5.5 mm dimensions at a temperature of 116° C. at a pressure of 500 psi (3.44 MPa) for a period of 10 minutes. The areal density (AD) of the panels is 0.75 lb/ft^2 (3.67 kg/m^2).

[0081] One of the flat panels is re-molded into a corrugated panel by pressing between matched steel dies at a temperature of 116° C. at a pressure of 500 psi (3.44 MPa) for a period of 10 minutes as described in Example 3. The diameter of the steel cylinders is 2.0 inches (50.8 mm). This produces a corrugation with 2.0 inches (50.8 mm) crest-to-crest spacing. The ratio T/t between the effective thickness of the corrugated panel and the 5.5 mm thickness dimension of the 50 layers of the impregnated KEVLAR 49® fabric constituting the panels is 2.49.

[0082] Both the composite article of the invention and the second 5.5-mm flat panel are subjected to ballistic testing by the method of MIL-STD 662E dated 22 Jan. 1987 using a 9 mm caliber, 124 grain FMJ bullet.

[0083] It is believed that the V50 velocity and the specific energy absorption of the composite article of the invention will be superior to the flat panel having essentially the same areal density regardless of the point of impact on the composite article of the invention.

Example 10

[0084] A ZYLON® fabric (Hexcel-Schwebel Style 530) is impregnated with 20 wt. % KRATON D1107 poly(styrene-isoprene-styrene) triblock thermoplastic elastomer. The ZYLON® fabric is a plain weave with 11.8×11.8 warp and fill yarns per centimeter. ZYLON® (poly(p-phenylene-2,6-benzobisoxazole)) yarns have a tenacity of 42 g/d and a tensile modulus of 1325 g/d.

[0085] Twenty-seven layers of the impregnated fabric are molded into two flat panels of 33 cm×33 cm×5.5 mm dimensions at a temperature of 116° C. at a pressure of 500 psi (3.44 MPa) for a period of 10 minutes. The areal density (AD) of the panels is 0.90 lb/ft^2 (4.41 kg/m^2).

[0086] One of the flat panels is re-molded into a corrugated panel by pressing between matched steel dies at a temperature of 116° C. at a pressure of 500 psi (3.44 MPa) for a period of 10 minutes as described in Example 3. The diameter of the steel cylinders is 2.0 inches (50.8 mm). This produces a corrugation with 2.0 inches (50.8 mm) crest-to-crest spacing. The ratio T/t between the effective thickness of the corrugated panel and the 5.5-mm thickness dimension of the twenty-seven layers of the impregnated ZYLON® fabric constituting the panels is 2.49.

[0087] Both the composite article of the invention and the second 5.5-mm flat panel are subjected to ballistic testing by the method of MIL-STD 662E dated 22 Jan. 1987 using a 9 mm caliber, 124 grain FMJ bullet.

[0088] It is believed that the V50 velocity and the specific energy absorption of the composite article of the invention will be superior to the flat panel having essentially the same areal density regardless of the point of impact on the composite article of the invention.

[0089] Having thus described the invention in rather full detail, it will be understood that such detail need not be strictly adhered to but that further changes and modifications may suggest themselves to one skilled in the art, all falling within the scope of the invention as defined by the subjoined claims.

1. A ballistic-resistant article of manufacture having a plurality of corrugations and comprising a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix, wherein the effective thickness T of the ballistic-resistant article, in proportion to the thickness dimension t of said plurality of layers of fibrous networks, is from about 1.2 to about 10, wherein

2. The ballistic-resistant article of claim 1 wherein said corrugations are vertically extending ridges and grooves formed alternately and having a smooth meandering waveform in a lateral direction.

3. The ballistic-resistant article of claim 1 wherein said corrugations are vertically extending ridges and grooves formed alternately and lying in essentially straight lines in a lateral direction.

4. The ballistic-resistant article of claim 1 wherein said corrugations are dimples and mounds in a planar neutral surface.

5. The ballistic-resistant article of claim 1 wherein the crest-to crest spacing L of said corrugations, in proportion to the thickness dimension t of said plurality of layers of fibrous networks, is from about 2 to about 30.

6. The ballistic-resistant article of claim 1 wherein each of said layers is comprised of a sheet-like array of fibers in which said fibers are aligned substantially parallel to one another along a common fiber direction.

7. The ballistic-resistant article of claim 5 wherein said layers have an arrangement in which the fiber alignment directions in selected layers are rotated with respect to the fiber alignment direction of another layer.

8. The ballistic-resistant article of claim 1 wherein, as measured by MIL-STD 662E dated 22 Jan. 1987, the specific energy absorption of a 9 mm, 124 grain FMJ bullet at the V50 velocity is more than about 10% greater than the specific energy absorption of a flat plate having the same layers of the same fibrous networks in the same matrix.

9. The ballistic-resistant article of claim 1 wherein, as measured by MIL-STD 662E dated 22 Jan. 1987, the specific energy absorption of a 9 mm, 124 grain FMJ bullet at the V50 velocity is more than about 20% greater than the specific energy absorption of a flat plate having the same layers of the same fibrous networks in the same matrix.

10. The ballistic-resistant article of claim 1 wherein a majority of said layers is comprised of fibers having a tenacity greater than about 17 g/d, a modulus of elasticity greater than about 300 g/d and an energy-to-break greater than about 20 J/g.

11. The ballistic-resistant article of claim 10 wherein said fibers are selected from the group consisting of polyethylene fibers, aramid fibers and polybenzazole fibers.

12. The ballistic-resistant article of claim 10 wherein said fibers are selected from the group consisting of polyethylene fibers, poly(p-phenylene terephthalamide) fibers and poly(p-phenylene-2,6-benzobisoxazole) fibers.

13. A ballistic-resistant article of manufacture comprising:

a) an element having a plurality of corrugations, a front face and a rear face, said corrugated element comprising a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix, wherein the effective thickness of said corrugated element in proportion to the thickness dimension of said plurality of layers of fibrous networks is from about 1.2 to about 10; and

b) a panel attached to at least one of said faces of said corrugated element.

14. The ballistic-resistant article of claim 13 wherein said panel is attached to said corrugated element at points that are spaced no closer than every alternate corrugation.

15. The ballistic-resistant article of claim 13 wherein the panel is selected from the group consisting of a ceramic, a metal, and a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix.

16. A ballistic-resistant article of manufacture comprising a front face, a rear face and a plurality of plies, each said ply having a plurality of corrugations and comprising a plurality of layers of high strength, high tensile modulus fibrous networks in a matrix,

wherein the effective thickness of each said corrugated ply, in proportion to the thickness dimension of the plurality of layers comprising the ply, is from about 1.2 to about 10, and wherein the direction of the corrugations in one ply are rotated with respect to the direction of the corrugations in another ply.

17. The ballistic-resistant article of claim 16 additionally comprising a panel forming at least one of the faces of said ballistic-resistant article.

18. The ballistic-resistant article of claim 16 wherein the ballistic-resistant article has out-of-plane curvature.

19. The ballistic-resistant article of claim 18 wherein the ballistic resistant article conforms to the surface of a human body.

20. The ballistic-resistant article of claim 1 wherein the ballistic-resistant article has out-of-plane curvature.

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