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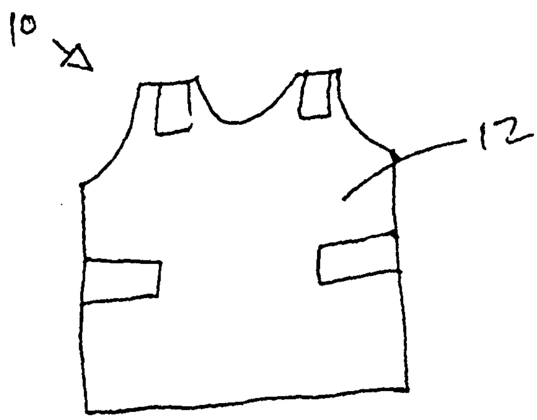
(57) Abstract

A composite element in an armored vehicle or armored garment includes a reaction–bonded ceramic matrix with ceramic fiber embedded therein. Preferably, the reaction–bonded ceramic matrix includes nitride–bonded silicon carbide, and the ceramic fiber includes silicon carbide. The matrix can additionally include nitride–bonded boron carbide. In a method of this invention, plies of non–woven, monofilament silicon carbide fiber are formed, and a slip including silicon carbide powder and silicon powder is cast around the plies to form a matrix around the plies. The silicon/silicon carbide matrix is then reaction–bonded to form a composite element of this invention.



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COMPOSITE ARMOR AND FABRICATION METHOD

RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application No. 60/127,245, filed March 31, 1999, the entire teachings of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

Conventional armor typically includes a monolithic element, such as aluminum oxide (Al_2O_3), silicon carbide (SiC) or boron carbide (B_4C), attached to a backing, such as KEVLAR para-aramid cloth (available from E.I. DuPont de Nemours, Wilmington, Delaware, USA), SPECTRA polyethylene fabric (available from Honeywell, Morristown, New Jersey, USA), fiberglass cloth, rubber, or aluminum honeycomb. Armor of this sort routinely is used for shielding vehicles, such as tanks, aircraft, space stations, etc., as well as for shielding individuals, including military personnel and police officers, when incorporated, for example, in bullet-proof vests.

In recent years, the idea of forming armor of a composite material, rather than of a monolithic material, has been explored. A principal advantage of using a composite material is that it can provide improved fracture toughness relative to monolithic materials. These efforts, however, have focused on hot-pressed composite materials. While hot-pressing is useful for forming a dense composite material, the process is expensive and is limited to forming simple shapes. Further, hot pressing typically requires the use of sintering aids, and the high temperatures required for hot pressing (typically greater than 1600°C) tend to degrade continuous fibers placed in the matrix.

SUMMARY OF THE INVENTION

A composite element of this invention is a component of an armor shell on a vehicle substructure or in an armored garment that can be worn to protect the wearer from projectiles. The composite element of this invention includes a reaction-bonded ceramic matrix with ceramic fibers embedded therein.

In a method of this invention, plies of non-woven, monofilament silicon carbide fibers are formed, and a slip including silicon carbide (SiC) powder and silicon powder is cast around the plies to form a matrix around the plies. The matrix is then reaction-bonded to form a composite element of this invention. Alternatively, the silicon carbide powder can be replaced, at least in part, with boron carbide (B_4C) powder. The composite element is then attached either to a vehicle substructure or to a garment to be worn by an individual to shield the vehicle/wearer from ballistics (*e.g.*, bullets, explosives and/or missiles, depending on the application).

The composite elements and methods of this invention offer a number of advantages in terms of cost, performance, and ease of forming. For example, reaction-bonded composite elements of this invention can be formed at less expense than hot-pressed composites, with the reaction-bonding process allowing for incorporation of continuous fiber reinforcement. Also, composite elements of this invention have the capability to withstand multiple ballistic impacts notwithstanding their high porosity relative to typical hot-pressed composites. In addition, reaction-bonded composite elements of this invention can easily be formed into a wide variety of shapes of complex geometry, offering far greater design freedom relative to hot-pressed composites and offering a better match to optimal shapes needed for vehicle and body armor. Further, the reaction-bonding process of this invention bonds the matrix particles at much lower temperatures and pressures than is required for hot-pressing or sintering.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

FIG. 1 illustrates an embodiment of an armored garment of this invention.

FIG. 2 illustrates an embodiment of an armored vehicle of this invention.

DETAILED DESCRIPTION OF THE INVENTION

This invention is generally directed to armored vehicles and armored garments that comprise at least one composite element including ceramic fiber embedded in a reaction-bonded ceramic matrix. The term, "armor," is used herein to refer to a protective sheathing designed to prevent ballistic penetration. Additionally the terms, "fiber" and "fibers," are used interchangeably herein to refer to either a single extended filament or a plurality of filaments. The terms, "armored garment" and "body armor" also are used interchangeably herein.

In preferred embodiments of a composite armor of this invention, the reaction-bonded composite element of this invention is bonded or otherwise secured either to a fabric, such as a KEVLAR or fiberglass cloth, for forming semi-rigid body armor or to a substrate, such as a slab of rubber or an aluminum honeycomb, to form a composite armor. In the case of body armor 10, as shown in FIG. 1, the composite element 12 is a component of a garment designed to shield the wearer of the vest from injury due to bullets and other ballistics. In the latter case, the composite armor 22 is then attached to a vehicle substructure 24, such as that of an aircraft, spacecraft, or earth-based vehicle (such as the tank 20 in FIG. 2), to shield the vehicle from bullets, missiles, and explosives.

Armored garments, or "body armor," of this invention can be of either a rigid or semi-rigid design. In rigid body armor, the composite element typically is a large, molded panel designed to cover certain portions of the human body. Semi-rigid armored garments typically include a plurality of composite elements in the form of relatively-small articulated plates reinforced with a woven ballistic material, *e.g.*, KEVLAR cloth.

The use of armored garments for protecting vital organs is particularly important. Accordingly, a preferred embodiment of this invention is a garment, such as a vest, that protects the torso. Armored garments of this invention offer protection not only against ballistics but also against clubs and other rigid objects that may cause injury during a battery or accident (*e.g.*, vehicular). Armor of this invention also protects against blunt trauma--which can pose a serious danger to a wearer of non-rigid armor, for example, due to deformation of the armor when impacted by a projectile such as a bullet--because the composite element of this invention is highly resistant to deformation.

Under the classification system for body armor established under Standard 0101.03 by the National Institute of Justice (NIJ), armor "types" ranging from Type I to Type IV have been established to indicate the level of threat that a given armor product is capable of defending against. Whereas fabric-based armor systems, such as those that use KEVLAR cloth, are typically used against threats from smaller-caliber ballistics, the "hard" armor of this invention is preferred for use as a Type III, III-A, or IV body armor against higher-level threats. Type III-A armor is designed to protect against .44 Magnum and submachine gun 9 mm bullets. Type III armor is designed to protect against high-powered rifle bullets. Finally, Type IV armor is designed to protect against "armor piercing" bullets.

In preferred embodiments, the ceramic fiber is formed of silicon carbide; the fibers form about 4% to about 10%, by volume, of a composite that includes SiC fiber and a bonded SiC or B_4C matrix. Where the composite element is to be used as vehicle armor or Type IV body armor system, a fiber content of about 6% to about 10%, by volume, is preferred. For Type III or Type III-A body armor (for protection against non-armor piercing munitions), a composite that can withstand multiple hits can be formed with a fiber content of about 4% to about 6% by volume.

Preferably, the fibers are SCS-6™ fibers, available from Textron Systems Corp. (Wilmington, Massachusetts, U.S.A.). The SCS-6™ fibers are manufactured from a carbon monofilament and have a circular cross-section with a diameter of 140 microns (μm). Alternatively, or in addition, 79-μm fibers (commercially available as SCS-9A™ from Textron Systems Corp.) may also be employed. In the SCS-6™ fiber, the carbon monofilament is approximately 35 μm in diameter. The fiber is coated with an approximately 17-μm-thick carbon-rich silicon carbide buffer via chemical vapor deposition of a feed of a silane blend, hydrogen, argon and propane. The buffer layer, in turn, is coated with an approximately 32-μm-thick stoichiometric silicon-carbide bulk layer, also applied by chemical vapor deposition. Finally, an approximately 3-μm-thick carbon-rich silicon carbide deposit is applied, also by chemical vapor deposition, as a surface coating on the silicon carbide bulk layer.

The reaction-bonded ceramic matrix in which the fibers are embedded preferably comprises nitride-bonded silicon carbide and/or nitride-bonded boron carbide. In the "reaction-bonding" technique, which is derived from methods for fabricating monolithic ceramics, at least one component of the matrix is chemically reacted with a liquid or gas. In this example, a blend of silicon carbide powders and silicon metal is consolidated by nitridation of the silicon metal, resulting in a Si_3N_4-bonded SiC matrix having continuous SiC filament reinforcements. The nitride-bonding process generally produces a matrix with higher porosity (typically between about 10% and about 20%) than that of hot-pressed or sintered materials. In an embodiment where the SiC-based matrix comprises approximately 20% silicon nitride by weight, the resultant porosity can be between about 14% and about 18%. Additionally, the matrix can also include cubic boron nitride. The matrix concentration of cubic boron nitride is preferably about 20% in a region that is selected, depending upon the characteristics of the ballistics that it is designed to shield against, to provide the greatest barrier to ballistic penetration. In one embodiment, this region extends 2 mm from the surface that is subject to impact. In other embodiments, this region is in an interior portion of the armor or extending from the inner surface, which is remote from impact so that the ballistic can be subject to initial shearing before reaching the cubic-boron-nitride-hardened region.

In a method of this invention, plies of non-woven, monofilament silicon carbide fiber are formed, and a slip comprising silicon carbide powder and silicon powder is cast around the plies to form a matrix. Next, the matrix is reaction-bonded to form a composite element. The composite element can then be attached to either a vehicle substructure to form an armored vehicle or to a garment to form an armored garment.

In one embodiment, the composite is formed starting with a slip of the following composition, with the approximate percentage of each component, by weight, indicated in parentheses: silicon carbide powder or a mixture of silicon carbide and boron carbide powders (70% to 75%), silicon powder (8% to 12%), red iron oxide and sodium silicate (1% to 3%) and distilled water (10% to 20%). The specific composition of a preferred slip, with SiC and silicon broken down by particle-size distribution, is as follows:

0.1 - 1.0 μm β-SiC particles	13.96%
1 - 2 μm β-SiC particles	7.49%
2 - 3 μm β-SiC particles	5.20%
3 - 4 μm β-SiC particles	2.54%
4 - 10 μm β-SiC particles	2. 54%
80 - 120 μm β-SiC particles	42.30%
5 - 10 μm silicon particles	8.46%
10 - 14 μm silicon particles	2.12%
red iron oxide	1.44%
sodium silicate	0.08%
water (distilled)	13.87%

The above-described slip is agitated and mixed by continuously rolling it in a sealed container on a motorized drum roller. Inside the sealed container are dense rubber balls used to assist in the mixing process.

A plaster mold is used to form the final shape of the composite element, which, in this case, is in the form of a plate. The height of the borders around the mold govern the thickness of the plate. Initially, a thin layer of the slip is poured into the mold, then separate plies of SCS-6 fiber are placed over the slip. The SCS-6 fibers are placed in alternating 0° and 90° orientations and can be equally spaced or spaced closer toward one side of the plate. Each ply of fiber is laid between alternating applications of the slip, with an application of slip above and below the beginning and ending plies of fiber. When the fiber additions are completed a final application of slip is poured to top off the mold.

The green body is removed from the plaster mold and dried in an oven set between 100° and 120°C. The dried plates are loaded into a furnace and placed under a vacuum. The temperature in the furnace is increased at a rate of 5°C/min. At 500°C, the vacuum system is isolated and the furnace is filled with nitrogen. The nitrogen pressure is maintained at 800 torr throughout the remainder of the nitriding cycle to convert the pure silicon metal to silicon nitride, thereby "nitride bonding" the silicon carbide matrix. At 950°C, the ramp rate is lowered to 2.5 °C/min until it reaches 1150°C, where the temperature is held for six hours. The temperature is then ramped to 1250°C at a rate of 0.42°C/min. The temperature is then held at 1250°C for six hours and then ramped to 1350°C at a rate of 0.28°C/min. Next, the temperature is held at 1350°C for eight hours and then ramped to 1395°C at a rate of 0.375°C/min. Finally, the temperature is held at 1395°C for six hours before the cycle is ended and then cooled to room temperature. The ceramic plates are removed from the furnace and , in some embodiments, are then machined with a diamond saw blade into the final required plate dimension.

The ceramic plate manufactured by the above-described process contains α-Si_3N_4 bonded silicon carbide with continuous silicon carbide fiber reinforcement. The density range is between 2.65 and 2.70 g/cc.

In alternative embodiments, particulate materials can be substituted to change the characteristic hardness and density of the ceramic plate. In one example, the composition of the slip is the same as that described in the table, above, except that 50-μm boron carbide particles are used in place of the 80-120 μm SiC particles. This substitution can be performed without substantially affecting the ballistic performance of the final nitride-bonded composite plate, while nevertheless lowering the density of the plate to 2.35 g/cm^3.

Where extreme hardness in the plate is desired, particles of cubic boron nitride, preferably of about 30 - 65 μm particle size, are substituted for a portion of the silicon carbide or boron carbide particles. Preferably, the cubic boron nitride forms about 20% of the slip, and this slip is added to the mold at a stage where the layer will be positioned where the hardest region is desired, typically at the surface. The resulting hardness of this region can be 40% to 50% harder than the remainder of the plate. Potential uses for such a hardened plate include Type IV body armor systems and vehicle armor systems that require greater ballistic performance.

While porosity is generally thought to reduce the fracture toughness of a material, the relatively-high-porosity composite elements of this invention are thought to perform favorably relative to the performance of denser, hot-pressed materials. The pores in the composite element of this invention are believed to serve as crack initiators that retard the dissipation of energy when the material is exposed to high impact, while fibers of the composite blunt cracks and absorb energy while holding the element together. Moreover, the carbon-rich surface coating of the fibers is believed to facilitate the crack-arresting feature of this invention. Consequently, composite elements of this invention have the capability to withstand multiple impacts from high-velocity projectiles without shattering.

EXPERIMENTAL

The present invention will now be illustrated by the following examples which are not intended to limit the scope of the invention.

Example 1

A composite element of this invention were formed in accordance with the above-described procedure. Specifically, the slip comprised silicon carbide powder (74%), silicon powder (11%), red iron oxide (1.5%), sodium silicate (<1%) and distilled water (14%). The fiber reinforcement formed 10 volume % of the matrix/fiber composite and were in the form of a pair of continuous fiber plies orthogonally oriented relative to one another. The composite element had a density of 2.7 g/cm^3 and a porosity of about 15%. The ultimate stress was measured at 137.5 MPa, and the flexural modulus was measured at 107.9 GPa in a four-point bend test conducted in accordance with American Society For Testing and Materials (ASTM) standard C1161-94. When a dynamic mechanical resonance (DMR) test, conducted in accordance with ASTM standard C134-97, was used, a higher reading (138 GPa) for the flexural modulus was obtained.

Example 2

In this example, nitride-bonded silicon carbide composites of this invention were formed as in the previous example, except that the fiber orientation was limited to a single direction. When used in this example, the four-point flexure test showed a strength of 172 MPa and a modulus of 127 GPa in the direction of the fibers. Again, when the dynamic mechanical resonance (DMR) test was used, a higher reading (154 GPa) for the flexural modulus was obtained.

Example 3

For comparison, a non-reinforced nitride-bonded silicon carbide matrix was formed in accordance with the previous examples, with the exception that fibers were not employed. The matrix was found to have an ultimate stress of 58 MPA with a modulus of 117 GPa when measured via the four-point flexure test. Once again, measurements obtained via the dynamic mechanical resonance (DMR) test provided a higher reading (124 GPa) for the flexural modulus.

EQUIVALENTS

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

CLAIMS

What is claimed is:

1. An armored vehicle having an armor shell including at least one composite element, the composite element comprising:
   a) a reaction-bonded ceramic matrix; and
   b) ceramic fiber embedded in the ceramic matrix.

2. The armored vehicle of claim 1, wherein the reaction-bonded ceramic matrix includes at least one member selected from the group consisting of nitride-bonded silicon carbide and nitride-bonded boron carbide.

3. The armored vehicle of claim 1, wherein the reaction-bonded ceramic matrix includes nitride-bonded silicon carbide.

4. The armored vehicle of claim 3, wherein the ceramic fiber includes silicon carbide.

5. The armored vehicle of claim 4, wherein the ceramic fiber is in the form of non-woven monofilaments.

6. The armored vehicle of claim 5, wherein the reaction-bonded ceramic matrix is porous.

7. The armored vehicle of claim 6, wherein the porosity of the composite element is in a range between about 10% and about 20%.

8. The armored vehicle of claim 5, wherein the amount of non-woven, monofilament ceramic fiber in the composite element is in a range between about 6% and about 10% by volume.

9. The armored vehicle of claim 5, wherein the non-woven, monofilament silicon carbide fiber has an average diameter in a range between about 79 μm and about 140 μm.

10. The armored vehicle of claim 9, wherein the non-woven, monofilament silicon carbide fiber has an average diameter of about 140 μm.

11. The armored vehicle of claim 5, wherein the non-woven, monofilament silicon carbide fiber is collimated in plies within the matrix.

12. The armored vehicle of claim 5, further comprising cubic boron nitride in the reaction-bonded ceramic matrix.

13. The armored vehicle of claim 12, wherein the cubic boron nitride is selectively concentrated within a region of the reaction-bonded ceramic matrix.

14. An armored garment including at least one composite element, the composite element comprising:

a) a reaction-bonded ceramic matrix; and

b) ceramic fiber embedded in the ceramic matrix,

the composite element being adapted to protect a wearer of the armored garment from ballistic penetration.

15. The armored garment of claim 14, wherein the reaction-bonded ceramic matrix includes at least one member selected from the group consisting of nitride-bonded silicon carbide and nitride-bonded boron carbide.

16. The armored garment of claim 14, wherein the reaction-bonded ceramic matrix includes nitride-bonded silicon carbide.

17. The armored garment of claim 16, wherein the ceramic fiber includes silicon carbide.

18. The armored garment of claim 17, wherein the ceramic fiber is in the form of non-woven monofilaments.

19. The armored garment of claim 18, wherein the nitride-bonded silicon carbide matrix is porous.

20. The armored garment of claim 19, wherein the porosity of the composite element is in a range between about 10% and about 20%.

21. The armored garment of claim 19, wherein the amount of non-woven, monofilament ceramic fiber in the composite element is in a range between about 4% and about 6%, by volume.

22. The armored garment of claim 19, wherein the non-woven, monofilament ceramic fiber is collimated in plies within the matrix.

23. The armored garment of claim 15, wherein the reaction-bonded ceramic matrix further includes cubic boron nitride.

24. The armored garment of claim 23, wherein the cubic boron nitride is selectively concentrated within a region of the reaction-bonded ceramic matrix.

25. The armored garment of claim 14, further including woven ballistic fibers that reinforce the composite element.

26. A method for forming a composite element and incorporating it in an armored vehicle, comprising the steps of:

a) forming plies of non-woven, monofilament silicon carbide fiber;
b) casting a slip including silicon carbide powder and silicon powder around the plies of non-woven, monofilament silicon carbide fiber to form a powder / fiber composition;
c) reaction-bonding the powder / fiber composition to form a reaction-bonded composite element; and
d) attaching the reaction-bonded composite element to a vehicle substructure, wherein the reaction-bonded composite element forms a shield around the vehicle substructure.

27. The method of claim 26, wherein the slip further includes boron carbide powder.

28. A method for forming an armored garment, comprising the steps of:
a) forming plies of non-woven, monofilament silicon carbide fiber;
b) casting a slip including silicon carbide powder and silicon powder around the plies of non-woven, monofilament silicon carbide fiber to form a powder / fiber composition;
c) reaction-bonding the powder / fiber composition to form a reaction-bonded composite element; and
d) attaching the reaction-bonded composite element to a garment that can be worn by an individual to shield the individual from projectiles.

29. The method of claim 28, wherein the slip further includes boron carbide powder.

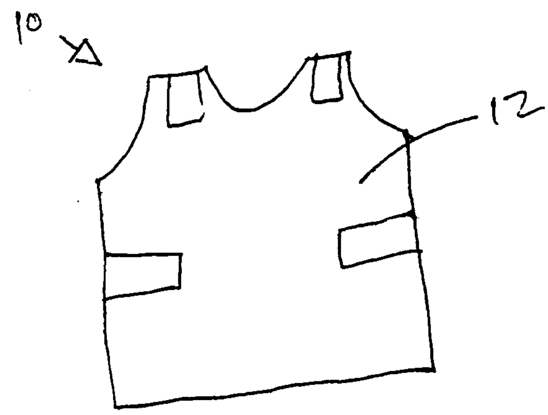

FIG. 1

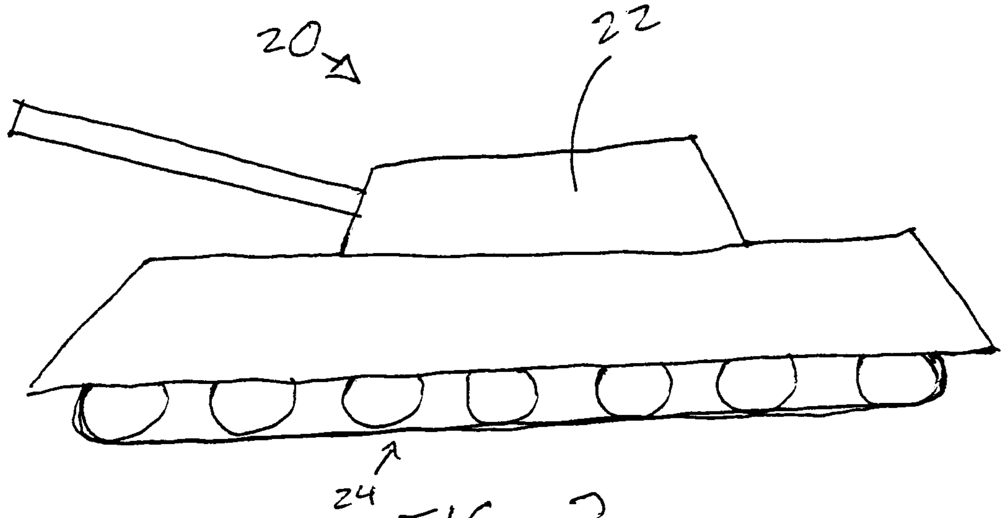

FIG. 2