TABLE 5-continued

Comparison of ballistic performance of STF-impregnated KEVLAR ® with dry silica-impregnated KEVLAR ®

Sample Target	Description	Sample Weight (g)	Impact Velocity (m/s)	Penetration Depth (cm)
G	4 ml STF impregnated in 4 layers of KEVLAR ®	7.9	244	0.886
E	8 ml STF impregnated in 4 layers of KEVLAR ®	13.9	253	0.675
X1	3 g dry silica impregnated in 4 layers of KEVLAR ®	4.9	252	1.42
X2	6 g dry silica impregnated in 4 layers of KEVLAR ®	7.9	234	1.22
X3	12 g dry silica impregnated in 4 layers of KEVLAR ®	13.9	225	0.89

Table 6 shows that varying the impregnation pattern of the target from layer-to-layer, and varying the pattern of impregnation within a single layer, can be used to enhance the ballistic performance of the fabric. Comparison of Target H to Target C demonstrates that including a few layers of KEVLAR® impregnated with STF can significantly enhance ballistic resistance over the equivalent number of neat KEVLAR® layers (Target C). Furthermore, Target I is composed of a small amount of STF impregnated into the KEVLAR® in a "striped" pattern. Comparison of Target I to Target J demonstrates that the impregnation of the STF into the target can be "patterned", i.e. need not be fully impregnated and still result in substantial increases in ballistic resistance. Further, comparison of the performance of Target I and Target J, both composed of 6 layers of KEVLAR®, shows that even a very small amount of STF impregnated into the fabric results in enhanced ballistic performance.

TABLE 6

Ballistic performance of targets with varying impregnation patterns within a fabric layer, and between fabric layers.

Sample Target	Description	Sample Weight (g)	Impact Velocity (m/s)	Penetration Depth (cm)
C	4 layers of KEVLAR ®	1.9	244	2.12
H	2 layers of neat KEVLAR ®, stacked on top of 8 ml of STF impregnated into 2 layers of KEVLAR ®	13.9	242	0.787
I	0.22 ml of STF impregnated into 6 layers of KEVLAR ® fabric, with a striped impregnation pattern in each fabric layer	3.18	254	1.4
J	6 layers of KEVLAR ®	2.82	254	1.7

Table 7 shows that similar enhancements in performance have been achieved with different particles and solvents impregnated into the KEVLAR ® fabrics:

Table 7 shows that similar enhancements in performance have been achieved with different particles and solvents impregnated into the KEVLAR® fabrics:

Table 7, sample K, which is composed of 450 nm silica particles coated with an adsorbed polymer, poly(vinyl alcohol) and dispersed in ethylene glycol, shows enhanced ballistic resistance comparable to the performance of sample A.

Table 7, sample L shows results for a shear thickening fluid composed of silica particles (450 nm) dispersed in a polymeric solvent, polyethylene glycol (PEG), where similar enhancement in ballistic performance is achieved as for the molecular ethylene glycol formulations.

Table 7, sample M shows a formulation using much smaller silica particles, 30 nm, in polyethylene glycol (PEG), which shows significant ballistic resistance that is comparable to samples with the larger particle sizes (450 nm).

Table 7, sample N shows nonspherical particles consisting of elliptically shaped calcium carbonate ellipsoidal particles in ethylene glycol. This formulation shows enhancement in ballistic resistance comparable to the spherical particles.

As shown the STFs can vary in carrier fluid type, particle type, and surface functionalization, but all STFs tested successfully enhance ballistic performance.

TABLE 7

Ballistic performance of impregnated KEVLAR ® targets with different types of STF

Sample Target	Description	Sample Weight (g)	Impact Velocity (m/s)	Penetration Depth (cm)
A	2 ml STF (450 nm spherical silica in ethylene glycol) impregnated into 4 layers of KEVLAR ®	4.8	243	1.23
K	2 ml STF (450 nm polymer-stabilized spherical silica in ethylene glycol) impregnated into 4 layers of KEVLAR ®	4.9	259	0.74
L	2 ml STF (450 nm spherical silica in polyethylene glycol) impregnated into 4 layers of KEVLAR ®	4.9	246	1.8
M	2 ml STF (30 nm spherical silica in polyethylene glycol) impregnated into 4 layers of KEVLAR ®	5.3	331	1.57
N	1.6 ml STF (anisotropic CaCO3 particles in ethylene glycol) impregnated into 4 layers of KEVLAR ®	4.8	244	0.48

The material can be used for advanced body armor, airbags, protective material, such as for engines and turbines or anywhere that there is a desire to dissipate the kinetic energy of a moving article. The material can also be used for bomb blankets, tank skirts, stowable vehicle armor, inflatable protective devices, tents, seats or cockpits, storage and transport of luggage, or storage and transport of munitions. The material can be used to fashion protective clothing, such as boots, which could stiffen to provide bodily protection against blasts, such as those caused by exploding land mines, and sudden impacts, such as those incurred upon landing by parachute, or in accidents. The material would have stab resistance properties and can be used to provide bodily protection against sharp instruments, such as knives or swords used in hand-to-hand combat.

All the references described above are incorporated by reference in their entirety for all useful purposes.

As can be seen from the above description, the present invention provides an improved fabric for use in dissipating the kinetic energy of a moving article. While the examples illustrate that the moving article is a bullet, the moving

vents should be environmentally stable so that they remain integral to the fabric and suspended particles during service.

The particles are suspended in the solvent and should produce a fluid that has the shear thickening property. Shear thickening does not require a dilatant response, i.e. it may not be associated with an increase in volume such as often observed in dry powders or sometimes in suspensions of larger particles (greater than 100 microns). The fluid may be diluted with a second solvent to enable impregnation of the fabric, and then reconcentrated through evaporation of the second solvent after impregnation, as long as the remaining impregnated fluid remains a flowable liquid with shear thickening properties.

The ballistic properties of woven fabrics, such as, but not limited to, KEVLAR® fabrics, are improved through impregnation with fluids that exhibit the shear thickening effect. At low strain rates, for example associated with normal motion of the wearer of a body armor system, the fluid will offer little impediment to fabric flexure and deformation. However, at the high strain rates associated with a ballistic impact event, the fluid will increase in viscosity and in doing so, enhance the ballistic protection of the fabric. The STF used in the targets is composed of particles suspended in a solvent.

EXAMPLES

In the following examples silica particles (Nissan Chemicals MP4540) were suspended in ethylene glycol, at a volume faction of approximately 0.57. The average particle diameter, as measured using dynamic light scattering, was determined to be 446 μm. Rheological measurements have shown that this STF undergoes a shear thickening transition at a shear rate of approximately 10^2–10^3 s^{-1}. Additionally, this transition is reversible, i.e. this liquid-to-solid transition induced by flow is not associated with particle aggregation, nor does it result in any irreversible change in the dispersion Full details regarding the preparation and Theological properties of the STF can be found in Lee et al., *J. Mat. Sci.*, 38 pps. 2825–2833 (2003) and Lee and Wagner *Rheol. Acta.*, 2002.

The KEVLAR® fabric used in all composite target constructions was 600 denier plain-woven Hexcel-Schwebel high performance fabric Style 706 composed of KEVLAR® KM-2 aramid fibers (poly-paraphenylene terephthalamide) with an areal density of 180 g/m^2.

Target Preparation

To facilitate impregnation of the STF into the KEVLAR® fabric, an equal volume of ethanol (22.0 dyne/cm) was added to the original ethylene glycol (surface tension=47.7 dyne/cm) based STF. This diluted STF was observed to spontaneously impregnate the fabric. Following impregnation, the composite fabric was heated at 80° C. for 20 minutes in a convection oven to remove the ethanol from the sample. The final composition of the impregnated STF is 57 vol % silica in ethylene glycol. Microscopy has confirmed that this process results in the full impregnation of the STF into the KEVLAR® fabric, as STF wetting is observed at the filament level (Lee et al., *J. Mat. Sci.*, 2002).

A schematic diagram of a ballistic target is given in FIG. **1**. Two pieces of 5.08 cm×5.08 cm aluminum foil (50 mm thickness) were used to encapsulate the targets **10**. The KEVLAR® layers were cut to 4.76 cm×4.76 cm, impregnated with varying amounts of STF per layer (2, 4, and 8 ml) as indicated, and then assembled into the targets **10**. To prevent leakage of STF out of the target assembly, heat-sealed polyethylene film (Ziplock bags sealed using a ULINE KF-200HC heat sealer) was used to encapsulate the targets.

All targets **10** were backed with a backing **20**. The backing **20** contained a single ply of unimpregnated KEVLAR®, glued to a 5.08 cm diameter copper hoop (0.635 cm wire diameter) using Liquid Nails adhesive (ICI), in order to help support the target during testing. In all cases the glued KEVLAR® layer, backing **20**, was immediately adjacent to the ballistic target **10**, with the copper hoop resting inside of the target mounting frame **30**. All subsequent descriptions of ballistic targets **10** will list only the KEVLAR® layers within the aluminum foil layers, and do not include this individual backing **20** KEVLAR® layer.

Ballistic Tests

The ballistic tests were performed using a smooth bore helium gas gun. All tests were performed at room temperature. The gun was sighted on the target center and the impact velocity was adjusted to approximately 244 m/s (800 feet per second "fps"). The exact impact velocity of each projectile **40** was measured with a chronograph immediately before impacting the target **10**. The projectile **40** is a NATO standard fragment simulation projectile ("FSP"), consisting of a chisel-pointed metal cylinder of 1.1 grams (17 grains) and 0.56 cm diameter (22 caliber). A 10.16 cm×10.16 cm×2.54 cm thick aluminum block **30** was cut with a recessed square hole to accept the 5.08 cm square target package as shown in FIG. **1**. The target was held in place using light pressure from spring clips located along its edge. The mounting block was then clamped onto a steel frame in line with the gas gun barrel.

A clay witness **50** was used to measure the depth of indentation (NIJ standard-0101.04, 2001) (FIG. **1**). Modeling clay (Van Aken International) was packed into a 15.24 cm×8.89 cm×8.89 cm wooden mold, compressed with a mallet, and cut into four 7.62 cm×4.45 cm square pieces. This process minimizes air bubbles or poor compaction in the clay witness. The molded clay block was held onto the back of the target using a strip of adhesive tape. When comparing the ballistic performance of different targets, higher performance is demonstrated by smaller measured values of depth of indentation, which indicate that more energy was absorbed by the target.

The deformation rate on the fluid during the ballistic event is estimated to be on the order of 10^4–10^5 s^{-1} (deformation rate=V/projectile diameter=244 m/s 0.056 m). This rate is expected to be sufficient to rigidize the STF, since it exceeds the critical shear rate for the STF.

Flexibility and Thickness Tests

Two-dimensional drape tests were performed to measure the flexibility of the targets, as shown in FIG. **2**. In all cases a 20 g weight **60** was used, and encapsulated ballistic targets were used as the test specimens **70**. Bending angle is reported as a measure of target flexibility, with larger angles indicating greater flexibility. Target thickness at the center of the targets was also measured with a micrometer.

Results

Table 1 compares the performance of targets A, B, and C: 2 ml of STF impregnated into 4 layers of neat KEVLAR®, 10 layers of neat KEVLAR®, and 4 layers of neat KEVLAR®, respectively. Targets A and B have comparable weights. However, target A, which is an STF KEVLAR® composite, exhibits better ballistic performance than target B, the neat KEVLAR® target. Furthermore, the STF KEVLAR® composite (A) has fewer layers of KEVLAR®, more

ADVANCED BODY ARMOR UTILIZING SHEAR THICKENING FLUIDS

GOVERNMENT LICENSE RIGHTS

The United States Government has rights in this invention as provided for by Army Research Laboratories, CMR contract nos. DAAD19-01-2-0001 and DAAD19-01-2-0005.

BACKGROUND OF THE INVENTION

Body armor is essential equipment for police and military. Currently, body armor is fielded only in specific high-risk scenarios, and is typically limited to chest and head protection. However, a significant percentage of battlefield injuries occur to the extremities, including arms, legs, hands, and neck. Armor for these extremities must offer protection from fragment and ballistic threats, without significantly limiting soldier mobility and dexterity.

Conventional body armor materials are typically comprised of many layers of polyaramid poly(phenylene diamine terephthalamide) fabric, sold by DuPont under the registerd name of KEVLAR®, with optional ceramic tile inserts. These materials are too bulky and stiff for application in extremities protection. A material is needed which can offer the equivalent ballistic performance of existing body armor materials, but with significantly more compactness and flexibility.

Shear thickening is a non-Newtonian flow behavior often observed in concentrated colloidal dispersions, and characterized by a large, sometimes discontinuous increase in viscosity with increasing shear stress (Lee and Reder, A. S. *TAPPI Coating Conference Proceedings*, p. 201, 1972; Hoffman, R. L., *J. Colloid Interface Sci.*, Vol. 46, p. 491, 1974; Barnes, H. A., *J. Rheol.*, Vol. 33, p. 329, 1989). It has been demonstrated that reversible shear thickening in concentrated colloidal suspensions is due to the formation of jamming clusters resulting from hydrodynamic lubrication forces between particles, often denoted by the term "hydroclusters" (Bossis and Brady, *J. Chem. Phys.*, Vol. 91, p. 866, 1989; Foss and Brady, *J. Fluid Mech.*, Vol. 407, p. 167, 2000; Catherall et al., *J. Rheol.*, Vol. 44, p. 1, 2000). The mechanism of shear thickening has been studied extensively by rheo-optical experiments (D'Haene et al., *J. Colloid Interface Sci.*, Vol. 156, p. 350, 1993; Bender and Wagner, *J. Colloid Interface Sci.*, Vol. 172, p. 171, 1995), neutron scattering (Laun et al., J. Rheol., Vol. 36, p. 743, 1992; Bender and Wagner, *J. Rheol.*, Vol. 40, p. 899, 1996; Newstein, et al., *J. Chem. Phys.*, Vol. 111, p. 4827, 1999; Maranzano and Wagner, *J. Rheol.*, Vol. 45, p. 1205, 2001a; Maranzano and Wagner, *J. Chem. Phys.*, 2002) and stress-jump rheological measurements (Kaffashi et al., *J. Colloid Interface Sci.*, Vol. 181, p. 22, 1997). The onset of shear thickening in steady shear can now be quantitatively predicted (Maranzano and Wagner, *J. Rheol.*, Vol. 45, p. 1205, 2001a, and Maranzano and Wagner, *J. Chem. Phys.*, Vol. 114, p. 10514, 2001) for colloidal suspensions of hard-spheres and electrostatically stabilized dispersions. This shear thickening phenomenon can damage processing equipment and induce dramatic changes in suspension microstructure, such as particle aggregation, which results in poor fluid and coating qualities. The highly nonlinear behavior can provide a self-limiting maximum rate of flow that can be exploited in the design of damping and control devices (Laun et al., *J. Rheol.*, Vol. 35, p. 999, 1991; Helber et al., *J. Sound and Vibration*, Vol. 138, p. 47, 1990).

The general features of containment fibers for use in energy dissipating fabrics are high tenacity and high tensile modulus. These materials are also considered ballistic materials. At the same time, in many applications, it may be desirable to utilize a fabric having the benefits of relative low bulk and flexibility. To achieve such properties, polymeric fibers may be used. The fibers which may be preferred include aramid fibers, ultra-high molecular weight polyethylene fiber, ultra-high molecular weight polypropylene fiber, ultra-high molecular weight polyvinyl alcohol fiber and mixtures thereof. Typically, polymer fibers having high tensile strength and a high modulus are highly oriented, thereby resulting in very smooth fiber surfaces exhibiting a low coefficient of friction. Such fibers, when formed into a fabric network, exhibit poor energy transfer to neighboring fibers during an impact event. This lack of energy transfer may correlate to a reduced efficiency in dissipating the kinetic energy of a moving object thereby necessitating the use of more material to achieve full dissipation. The increase in material is typically achieved through the addition of more layers of material which has the negative consequence of adding to the bulk and weight of the overall fabric structure.

Among the most common uses for these so-called containment fabrics are in the use of body armor, and windings surrounding the periphery of turbine engines such as those found on commercial aircraft. Such an application is disclosed in U.S. Pat. No. 4,425,080 to Stanton et al. the teachings of which are incorporated herein by reference. The fabric is intended to aid in the containment of a projectile which may be thrown outwardly by rotating parts within the engine in the event of a catastrophic failure.

While the overall energy dissipating capacity of the fabric windings surrounding the engine is important, minimizing the thickness of the windings is also critical. Furthermore, economic considerations dictate that the number of fabric layers utilized for this purpose cannot be excessive. Thus, an effective containment structure should not require an excessive number of fabric layers to achieve the necessary levels of energy containment. It has been determined that the seemingly conflicting goals of improved kinetic energy containment and reduced material layers can, in fact, be achieved by improving the energy transfer between the adjacent fibers or yarns at the location of impact in the fabric network.

Several techniques are known for increasing the energy transfer properties between fibers or yarns but each of these known techniques has certain inherent deficiencies. One known method is to roughen the surface of the fibers or yarns by sanding or corona treatment. However, such roughening is believed to have limited utility due to the resultant degradation in the fiber.

Another method of increasing energy transfer between adjacent fibers or yarns is to coat the fabric with a polymer having a high coefficient of friction. One deficiency in this practice is the formation of fiber-to-fiber bonds. Such bonding may result in stress reflections at yarn crossovers during impact by a moving article, which cannot be transferred away from the impact region. Another deficiency is the large weight gain typical of coatings, which may be ten percent or more. A further limitation of this approach is a significant decrease in fabric flexibility due to the addition of the relatively stiff polymer coating. A related method is to use a sticky resin that creates adhesion between the fibers, as disclosed in U.S. Pat. No. 1,213,118 to Lynch, but this technique has the same inherent deficiencies of fiber to fiber bonding and increased weight as exhibited by coatings.

Fig. 1.

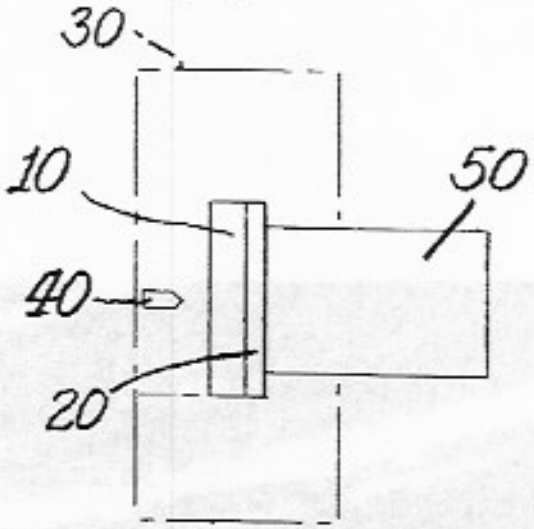
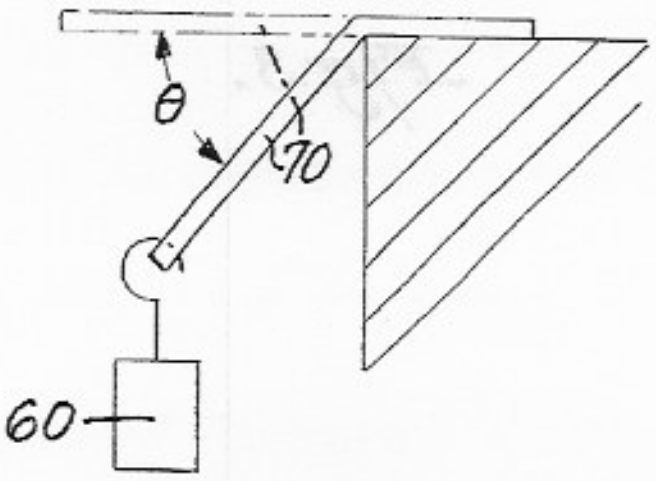


Fig. 2.



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(54) **ADVANCED BODY ARMOR UTILIZING SHEAR THICKENING FLUIDS**

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See application file for complete search history.

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(57) **ABSTRACT**

An armor composite material has been invented which contains a ballistic fabric which has been impregnated with shear thickening fluid. This invention offers a ballistic resistant material that is more flexible and less bulky than comparable, conventional ballistic fabric. The invented material offers superior ballistic performance compared to conventional ballistic fabric-based materials of equal thickness. The invented material can be applied to applications requiring armor that is compact and/or flexible, such as body armor, protective clothing and flexible protective devices and shields, and stab resistant clothing and devices.

13 Claims, 2 Drawing Sheets