Soft Body Armor for Law Enforcement Applications

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ABSTRACT
This paper focuses on the development of a novel ballistic protection composite which can provide both cut resistance and impact protection. The ballistic shield is made by sandwiching high strength, impact resistant, multi-layered woven fabrics between a leather strike face layer and a needlepunched fabric layer that offers protection upto Level IIIA and cut resistance. The needlepunched fabric when punched into the ballistic layer(s) pushes the fibers in the Z direction providing enhanced structural coherence and strength. Three different high performance fibers (Kevlar®, Spectra® and Twaron®) were used to make the composite. Ballistic tests were performed using V50 ballistic requirement based on NIJ standard. The availability of leather layer reduces the velocity of the impact and aides with the blunting of the bullet. A new phenomenon, "mushrooming" of the bullet has been observed. Results on the ballistic protection capabilities of different strike and impact resistant composite chest shields are presented in this paper.

INTRODUCTION
Recent terrorist attacks in Mumbai, India[1] and the release of the timely report [2] by the Commission on Prevention of Weapons of Mass Destruction have heightened the importance of countermeasures to terrorism. As is evident from these recent attacks, it has become clear that improvised explosive devices and other weapons of mass destruction can readily be available to terrorists with minimum investments. Therefore, it has become an immediate and important issue around the world to develop countermeasures to terrorism. As in all life-threatening situations, law enforcement personnel and first responders are the first line of protection, and hence personnel protective materials such as helmets, ballistic chest shields, boots, etc., occupy a prominent role in the front line of defense. Not only such materials are important in civilian theaters, these are extremely vital for warfighters in battlefields. Ever since the start of Iraq war, more than 4663 soldiers have lost their lives. It has been reported that majority of deaths in the recent Iraq war has been due to hostile firing and improvised explosive devices [3].

Although there are protective materials such as heavy weight ceramic shields with excellent protective capabilities [4], the lack of much needed comfort to the users is a major impediment for their fullest possible utilization. According to FBI Uniform Crime Report, from 1998 to 2008, 543 law enforcement officers were killed by firearm related incidents while performing their duty [5]. 67% of these officers were geared with ballistic proof vest when they were killed. It is evident from these deaths, that there is a high priority need for better performing armors that have higher protection levels than those, which are currently being used and at the same time have additional features such as strike resistance and enhanced comfort. More importantly, in addition to the ballistic materials, law enforcement personnel encounter attacks from sharp edged weapons such as knives, where resistance to cuts or strikes become an important requirement.

Initially, the concept of stopping a bullet from hitting the target was by trapping and dispersing its energy inside multi-layered fabric that were made using the strongest fibers available in the market like p-aramids (Kevlar®). But today due to advancement in technology and availability of high velocity bullets, the idea of "trapping-in" does not work effectively[4]. Therefore driven by the need for light-weight, high strength and chemically inert fibers for ballistic proof materials, fibers like Spectra® and Twaron® which can successfully stop bullets at higher velocities were developed. The gel spun ultra-high molecular weight polyethylene fiber (Spectra®) is lighter in weight with specific gravity less than one and is ten times stronger than steel. The p-aramid fiber, poly-paraphenylene terapthalamide (Twaron®) similar to Kevlar® is five times stronger than steel and resistant to temperature and chemicals. *Table I* shows the properties of these three fibers that were used in our study [6-8]. As a comparison, characteristics of apparel grade fibers such as nylon and PET are given which clearly show that the tenacity and tensile modulus are quite high for high performance fibers.

Tam and Bhatnagar [7] have reviewed the details of different high performance fibers such as Nomex®, polybenzimidazole (PBI), polyphenylenebenzobisoxazole (PBO), ultra high molecular weight polyethylene and aramid fibers. They have highlighted the main requirements for obtaining a high-performance fiber, they are: a) high degree of molecular orientation along fiber axis; b) very high molecular weight and c) high crystallinity.

TABLE I. Fiber Properties [6-8].

Fiber/ Properties	**Density (g/cc)**	**Moisture Regain (%)**	**Tensile Modulus cN/tex**	**Breaking Tenacity (g/tex)**	**Breaking Elongation (%)**	**Melting Point (°C)**
Kevlar®149	1.44	3.6	11,500	238.52	1.5-4.0	**482.22***
Twaron®	1.45	6.5	7,500	200.72	3.6	**500***
Spectra®2000	0.97	<0.1	12,000	342.03	2.9	**148.89**
PET	1.38	0.4	998	25.2-50.41	24-42	**250**
Nylon 6	1.14	2.8-5.0	400	31.50-64.81	17-45	**215**

* *Does not melt, begins to decompose*

As is evident from the aforementioned brief discussion, there is a plethora of literature available on the chemistry, synthesis and properties of these high performance fibers for ballistic protection. However to the best of our knowledge, there is limited information available on the development of lightweight anti-ballistic materials that have superior logistics and practical advantages.

In particular, there is an ongoing interest in lightweight ballistic proof materials with strike resistance. Such strike face antiballistic shields are needed by law enforcement personnel and first responders who are in the front line of defense against threat situations. Most recently, research at Texas Tech University has focused on developing lightweight ballistic chest shields that can provide enhanced protection due to the presence of strike face and abrasion resistant layer [9,10]. Ritter's work features the Core Matrix Technology™ wherein fibers from carded and cross lapped batting are mechanically interlocked into ballistic woven layers to develop 3-D, flexible, high performance and lightweight anti-ballistic panels. The mechanical bonding increases the z-directional strength by resisting the movement of yarns in the ballistic layers during the penetration of bullet and hence can reduce the blunt trauma and delamination of the layers. Such ballistics shields are predominantly meant for law enforcement personnel and first responder community. Ritter's work focuses only on enhancing the z directional strength by punching fibers into woven antiballistic layers and does not involve strike face layer for imparting additional functionalities such as cut resistance [9,10]. In another patented work, by Field and Soar, soft body armor was made by vertically packing layers containing cross plied unidirectional tape (Spectra Shield™) and woven ballistic fabric layer made of aramid fiber in a 2:1 ratio. This design has been claimed to reduce the total number of ballistic layers required to achieve protection from threat levels IIA, II and IIIA and have also proved to reduce the overall weight of the armor by 20% [14]. Field and Soar's work does not also focus on the abrasion resistance or strike proof layers. The study carried out at Texas Tech University focuses on providing a strike resistant layer to impart additional protection from sharp objects. The strike face layer is a finished apparel grade leather. The other side of the multilayered antiballistic composite consists of a staple fiber needlepunched fabric. This fabric can be needlepunched to a single or multiple layers of antiballistic woven fabrics. Although, the current study does not focus on the needlepunching of the staple fiber fabric layer into the antiballistic fabrics, this layer can be used to enhance the strength and coherency of the multilayered composite and can also serve as moisture transport layer. The usefulness of the staple fiber layer to the performance of the overall composite is outside the scope of this paper and will be a subject for an additional paper. Results todate show that the leather-antiballistic layers-staple fiber fabric composite can serve as a chest shield providing protection upto Level IIIA. It should be pointed out that, the level of protection depends on the number of anti-ballistic layers, type of high performance fiber used, the strike face material and the type and method of bonding. In this study, in addition to developing soft body armors, we have endeavored to carryout ballistic tests to generate ballistic data to prove the usefulness of the soft body armor chest shield as a

Level IIIA product. An experimental set has been fabricated to do the ballistic testing and the results are reported in the following sections of the paper. The development of an antiballistic chest shield with a strike face leather layer and ballistic results are the focus of the work. Ballistic protective shields developed in the study uses three different high performance fabrics: 1) Kevlar®; 2) Spectra® and 3) Twaron®. Details of the composites developed and their ballistic test results are delineated in the following sections of the paper.

EXPERIMENTAL

Materials

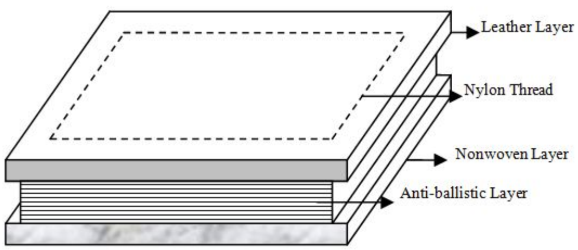

FIGURE 1. Cross Section of Ballistic Chest Shield[9].

TABLE II. Construction Details of Samples.

No. of Ballistic Layers	Weight (g/m^2)	Fiber Used	Fabric Weave	Type of Bonding
20	4491.8	K, S, T	Plain	Stitch
23	4931.2	K, S, T	Plain	Stitch
26	5517.1	K, S, T	Plain	Stitch
40	8202.4	K, S, T	Plain	Adhesive
50	10155.4	S	Plain	Adhesive

K –Kevlar®, S-Spectra®, T –Twaron®

Figure 1 shows the cross section of the three layered ballistic shield [9]. The top layer consists of apparel grade leather obtained from Hidehouse, Inc., Napa, CA. This layer provides the strike resistance and helps in the quick dissipation of ballistic impact from the bullet to the antiballistic layers. This is one of the aspects of novelty of the soft body armor technology that makes it different from Ritter's technology [11, 12]. The bottom layer consists of a needlepunched polyester nonwoven fabric (30 g/m^2), developed at Texas Tech University's Nonwovens and Advanced Materials Laboratory, Lubbock, TX. As delineated above, this layer can serve to enhance the structural coherence by providing Z directional strength where this layer is needlepunched into antiballistic layer(s). Additionally, the staple fiber needlepunched layers can also help with the transport of moisture. The evaluation of moisture transport characteristics is not the focus of the paper. In addition, the moisture transport nonwoven layer can also act as a cushioning layer which reduces the adverse effects of blunt trauma depending on the thickness and its weight. The middle antiballistic component consists of numerous plies (20, 23, 26, 40 and 50) of woven fabrics each weighing 203 g/m^2, obtained from Hexcel Inc., Anderson, SC made using three different high performance fibers namely: 1) Kevlar®; 2) Spectra®; and 3) Twaron®. The number of antiballistic layers varies according to the level of protection required. All three layers: leather, antiballistic fabrics and the nonwoven layer were either sewn together with nylon threads or glued using industrial grade adhesive spray obtained from 3M Corporation. *Table II* shows the weight and construction details of 20.32 cm x 27.94 cm ballistic chest shield composite that were used for ballistic testing.

Experimental Method

The ballistic performance of the samples was tested using Test for V_{50} Limit in accordance with NIJ Standard 0101.04 [10] at the testing facility that was set-up at Fort Worth, Texas as shown in *Figure 2*. This testing facility was built from scratch with help of Bellator Group, Fort Worth, Texas. This test aims to evaluate the ability of the body armor composite to resist free flying high velocity projectiles. The V_{50} ballistic limit is determined as the striking velocity at which 50% of the individual impacts will result in complete penetration. *Figure 3* illustrates the experimental set-up used to determine the V_{50} ballistic limit. *Table III* delineates the performance requirements as per the NIJ Standard for different protection levels [10]. For example, when the armor stops a bullet (9 mm Full Metal Jacketed bullet, Copper/Lead core cylinder, 124 grain) that travels at a speed not less than 341.4 m/s is qualified to provide Level IIA protection.

FIGURE 2. Ballistic Test Set-up.

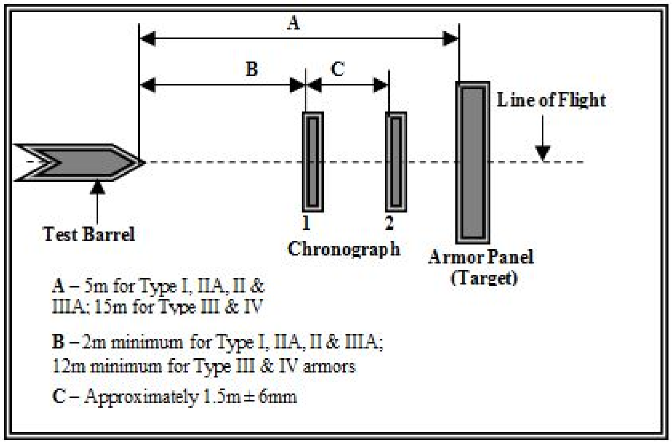

FIGURE 3. V_{50} Ballistic Limit Test Set-up.

TABLE III. NIJ Standard 0101.04 [13].

Armor Protection Level	**Test Round**	**Test Bullet**	**Bullet Weight (g)**	**Reference Velocity (±9m/s)**	**BFS (mm)**
I	1	.22 caliber LR LRN	2.6	**329.2**	44
	2	.380 ACP FMJ RN	6.2	**321.6**	44
IIA	1	9 mm FMJ RN	8.0	**341.4**	44
	2	.40 S&W FMJ	11.7	**321.6**	44
II	1	9 mm FMJ RN	8.0	**367.3**	44
	2	.357 Mag JSP	10.2	**435.9**	44
IIIA	1	9 mm FMJ RN	8.0	**435.9**	44
	2	.44 mag SJHP	15.6	**435.9**	44
III	1	7.62 mm NATO FMJ	9.6	**847.3**	44
IV	1	.30 caliber M2 AP	10.8	**877.8**	44

BFS: Maximum depth of back-face-signature allowed

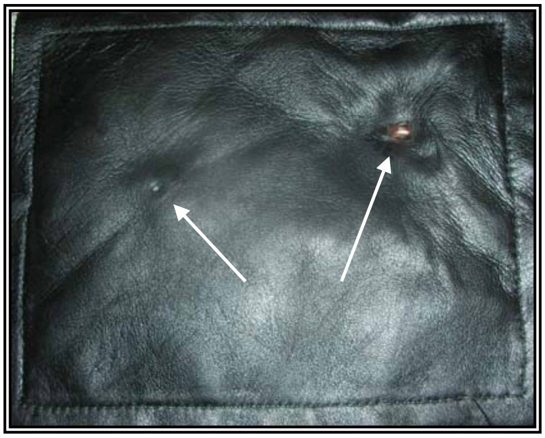

FIGURE 4. Bullets Trapped by the Armor.

FIGURE 5. Usefulness of Leather Layer.

FIGURE 6. “Mushrooming” of Bullets.

RESULTS AND DISCUSSION

Table IV shows the antiballistic performance results of the different ballistic chest shields as given in *Table II*. A total of 16 samples were tested. All of these samples had similar needlepunched fabric as the bottom layer and apparel grade leather as the strike resistance top layer. The variations among different samples were in the type and the number of antiballistic layers and the method of bonding. It is evident that, sample with 20 plies of antiballistic fabrics provide Level I protection. Samples with 23 and 26 plies provide Level IIA protection. 40 plies of Kevlar® and Twaron® samples that were glued together with adhesive spray and had leather on the top provide Level IIIA protection. This is clearly evident by the indication of partial penetration “P” in those samples that have successfully offered necessary protection at respective levels. For example, in the case of T26L sample that has 26 layers of Twaron® with leather successfully prevented the complete penetration of .357 magnum bullet at a velocity of 435.9 m/s showing it can very well offer Level IIA protection.

TABLE IV. V_{50} Ballistic Limit Test Results.

S.No.	Sample Code	Bullet Type	Velocity (1) m/s	Velocity (2) m/s	Mean m/s	P/C	Protection Level
1	K20	.380	-	-	-	P	I
		.22LR	380.4	383.4	381.9	P	
2	S20	.380	387.1	-	387.1	P	I
		.22LR	338.9	342.6	340.8	P	
3	T20	.380	221.9	222.8	222.4	P	I
		.22LR	375.8	386.8	381.3	P	
4	K20L	.380	289.1	289.3	289.2	P	I
		.22LR	389.2	-	389.2	P	
5	S20L	.380	-	-	-	P	I
		.22LR	380.7	385.3	383	P	
6	T20L	.380	281.5	-	281.5	P	I
		.22LR	354.8	365.2	360	P	
7	K23L	.357Mag	398.7	405.1	401.9	P	II
		9mm	360	364.5	362.3	P	
8	S23L	.357Mag	410.3	410.3	410.3	P	Failed
		9mm	360.9	360.3	360.6	C	
9	T23L	.357Mag	418.2	403.6	410.9	P	II
		9mm	354.8	359.4	357.2	P	
10	K26L	.357Mag	398.1	402.3	400.2	P	II
		9mm	358.7	361.5	360.1	P	
11	T26L	.357Mag	392.9	392.6	392.8	P	II
		9mm	357.8	356.3	357.1	P	
12	K40GL	.223	1003.1	997.6	1000.4	C	Failed
		.44Mag	457.2	457.2	457.2	P	
13	S40GL	.223	1014.4	-	1014.4	C	Failed
		.44Mag	474.6	-	474.6	C	
14	T40GL	.223	987.2	987.9	987.6	C	IIIA
		.44Mag	413.6	-	413.6	P	
15	S50GL	.223	987.2	-	987.2	C	Failed
		.30	555.7	-	555.7	C	
16	S50G	.223	-	-	-	C	Failed

Figures 4 and 5 show the advantages of having leather layer which helps in dissipating the impact from bullet. *Figure 5* shows the resistance offered by the strike resistance leather layer, which is evident by the distribution of impact stress. Visually one can see the "pushing away" of the leather structure away from the focal point of the impact. Leather layer offers the first line of resistance for the bullet. In addition, leather has high abrasion resistance and hence it can also provide good resistance to strikes and cuts. In addition to passing the required V_{50} ballistic limits for respective protection levels, the ballistic chest shields also fare well in obstructing the flight of the bullet which results in "*mushrooming*" of bullet heads, as shown in *Figure 6*. Blunting of the bullet heads after impact shows that the abrasion resistant antiballistic composites with the presence of additional components such as leather or any other strike resistant films can provide additional functionalities and enhance the overall performance of antiballistic chest shield. Further investigations including the "back face deformation," which will show the effect of blunt trauma on the human body will be investigated soon. Physical examination of the soft body armor shields show that they are flexible unlike rigid ceramic shields.

As is evident from *Table IV*, those ballistic chest shields which allowed the full penetration of bullets are marked by "C" and failed the V_{50} ballistic test at respective protection levels. On the other hand, those shields that prevented the full penetration of bullets are marked by "P" and are said to have passed the NIJ standard at respective protection levels.

CONCLUSIONS

Given the terrorists' threats around the world, it is extremely vital for the textile, materials science and defense communities to come together and find new products to counter threats from ballistics and WMD. The work reported here is aimed at an important issue, to develop a next generation soft body armor shield that can be of use to law enforcement personnel and first responders. The soft body armor technology reported here not only can provide ballistic protection, but also can provide strike resistance and protect law enforcement personnel from sharp objects due to the presence of leather layer on the top. The needlepunched fabric on the other side of the composite can provide the z directional strength to the composite enhancing the overall coherence and restricting the slippage between high performance fabric layers. Results indicate that the ballistic protection capabilities depend on the characteristics of the high performance fiber, structure of the antiballistic layer, the number of antiballistic layers and the method of bonding. The study reported in this paper shows that the addition of strike face material such as leather also plays important roles in slowing the velocity of the bullet and providing additional capabilities such as cut resistance. In the case of first responder situations, there could be possibilities of stab incidence for which the leather layer on the top could be beneficial. Specific results from the study shows that, 40 layers of antiballistic fabrics in the chest shield composite can provide protection upto Level IIIA.

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