Relationship Between Tensile Properties and Ballistic Performance of Poly(ethylene naphthalate) Woven and Nonwoven Fabrics

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ABSTRACT: In this study, we investigated the effect of tensile properties of poly(ethylene naphthalate) (PEN) yarns on the ballistic performance of woven and nonwoven soft and composite armors. The results of ballistic tests of PEN armors were compared with Kevlar 49 armors as a reference. Based on these results, the Cunniff's equation was revised by removing the fiber elongation at break to predict the relationship between tensile properties and ballistic performances of PEN fibers. The calculations showed that by increasing tenacity of PEN fibers from 8.5 g/den (commercial product) to 12.5 g/den (strongest up to date PEN fibers produced by a novel melt spinning process discovered by our research group), the weight ratio of PEN to Kevlar 49 decreased from 1.8 to 1.35 with the same ballistic performance. Contrary to the results of the soft armors, composite armors made of high modulus PEN woven fabric showed a 17% lower ballistic resistance compared to the composite armor made of low modulus PEN woven fabric. The results of ballistic tests indicated that high tenacity PEN fibers produced in this research could have potential in soft and composite armors, and high velocity impact applications or improve performance of PEN in its current applications. © 2012 Wiley Periodicals, Inc. J Appl Polym Sci 125: 2271–2280, 2012

Key words: poly(ethylene naphthalate); ballistic performance; woven fabric; nonwoven fabric; tensile properties

INTRODUCTION

Development of high strength and high modulus fibers has led to the use of fabrics for impact related applications such as bullet resistant vests or body armor. The impact and perforation properties of fabric and compliant laminates depend on a number of parameters including: (a) the properties of the yarn (high tensile and compressive properties, good temperature resistance, high impact properties, good adhesion to the matrix, and low density); (b) the fabric structure (i.e., type of weave, number of filaments per yarn, denier, weave density, and nonwoven); (c) the projectile geometry and velocity; (d) the interaction of multiple plies; (e) the far-field boundary conditions; (f) friction between yarn and projectile; and (g) type of resin used for laminating.[1]

The use of high performance fibers such as Kevlar, PBO, and Spectra/Dyneema in ballistic applications has been widely reported. The rigid molecular structure of PEN compared to other aromatic polyesters leads to significant improvements in many properties such as tensile, thermal, electrical, chemical resistance, outstanding gas barrier resistance, thermal and dimensional stability of PEN fibers.[2–5] PEN fibers have been commercially available from several producers including Teijin in Japan, Performance Fibers in the USA and Europe, Kosa in Europe, and Hyosung in Korea in many applications such as tire reinforcement and belting.[6,7]

This article aims at the ballistic performance of PEN materials in different forms of such as soft, composite, and hybrid armors. Therefore, in the next parts of the introduction, the studies on ballistic performance of soft, composite, and hybrid armors will be reviewed, which will be used in analysis of the results of this articles.

Soft armors

Although tensile strength, modulus, and strain-to-failure of yarn each have an important role in ballistic performance, no individual property can control ballistic performance of the fabric. Prosser et al.[8] noted that if the ballistic performance was based on yarn toughness, nylon would be a better performer than Kevlar, but it is not. Also, when the performance of high strength polypropylene was compared to nylon having two-thirds the strength, the nylon was a better

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This article is dedicated to Professor John Cuculo who recently passed away. He pioneered the work on high performance polyester fibers.

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performer.[9] The melting of thermoplastic polymers is a limitation in ballistic applications and heat resistant fibers hold better promise in ballistic applications. PEN has higher melting and glass transition temperature as compared to Nylon and PET. Cuniff developed an equation based on fiber properties to predict ballistic performance of fibers. The U^* is defined as the product of the specific fiber toughness multiplied by its strain wave velocity [eq. (1)][10]:

$$U^{*1/3} = \left(\frac{\sigma\varepsilon}{2\rho}\right)\sqrt{\frac{E}{\rho}} \qquad (1)$$

where σ is the fiber ultimate tensile strength, E is fiber modulus, and ε is the fiber ultimate tensile strain. The relationship between the mechanical properties of a yarn and the ballistic performance of a plied fabric is rather complex. There are other factors that should also be considered such as compressive properties, temperature resistance, inter fiber friction, and interaction between layers.

The response of a material during an impact test involves the combination of local (close to the projectile contact point) and global behavior of the material, which depends on impact velocity, projectile properties, target size, and boundary conditions.[11,12] There is debate between researchers about the most significant factor determining the nature of the impact response. The important factors are the impact velocity,[13–17] the mass ratio of projectile to target[18,19] and the ratio of local contact frequency to structural frequency of the target.[20] In a ballistic test (high velocity), the response of structure is governed by the local behavior of material, and global response becomes much less important.[21] After the projectile hits the fabric, the elastic and transverse waves expand with time, increasing the energy stored in the fabric until the projectile is stopped or perforates the material.[22,23] Although, by increasing projectile velocity locally response becomes more important. Obviously, it does not mean that the behavior at high velocity is necessarily different from that at low velocity impact, which the case is studied by some researchers.[16,17,24–28] The weight and velocity of projectiles are the key elements responsible for the kinetic energy (KE) associated with the bullet. The KE of the bullet can be calculated from eq. (2)[28]

$$\mathrm{KE} = \frac{1}{2}mV^2 \qquad (2)$$

where m is the mass of the projectile and V is the speed of the projectile.

Composite armors

In comparison to the soft armor, different types of damaging events occur during impact at high impact velocity in composite materials such as delamination, matrix cracking, fiber breakage, shear plugging, hole expansion, and friction. Two types of matrix cracks (transverse shear and bending cracks) were identified during both static and dynamic impact.[29–31] The failure modes of laminated composites at different impact velocities are brittle and tough. The brittle systems tend to delaminate with a very little growth, whereas tough systems are steadier with controlled delamination growth. If bending increases more than what caused by delamination, this ultimately leads to fiber breakage.[32] Delamination of the compliant laminate allows the fibers to extend to failure. However, depending on application, a certain degree of structural stiffness may be warranted, thus increased fiber-matrix adhesion may be used. The first few layers in multiple ply armor systems behave inelasticly and the remaining layers behave elasticly.[32]

Nonwoven armors

In addition to mechanical performance, some other important factors for ballistic protective materials are low weight, flexibility, and physiological comfort.[33] The woven fabrics and laid-up filament (Shield) are relatively heavy and thick, so they are not sufficiently flexible and light weight for use in all ballistic armors which exhibit better ballistic properties than present light weight materials.[34] Therefore, nonwoven fabrics have the advantages of light weight and flexibility in ballistic applications.

Needle-punching is a simpler operation than weaving, and a variety of properties can be obtained in the nonwoven by varying the process conditions.[34] A 1966 US Department of Defense study found that a needle-punched structure containing ballistic resistant nylon could be produced at one third the weight of a woven fabric, while retaining 80% of its ballistic resistance.[34] The needle-punched nonwoven made from blended 50/50 Kevlar and high-density polyethylene showed properties superior to the 100% Kevlar plain woven fabric.[35] The other example is a needle-punched fabric composed of HMPE staple fibers, which is mainly used for protection against fragments resulting from exploding bombs and shells.[36]

In this study, the hydroentanglement process was used for making nonwoven from PEN fibers. The hydroentanglement process is attractive because of the ability to obtain high levels of entanglement in light weight webs. In the hydroentangling process, fibers twist around their neighbors and/or interlock with each other by means of water jets having velocities up to 350 m/s.[37]

Hybrid armors

Hybridization of armors is another interesting area for improving ballistic performance using combinations

TABLE I
Mechanical Properties of PEN and Kevlar Yarns

Sample	Denier /No. of filaments	Tenacity (g/den)	Modulus (g/den)	Elongation at break (%)
Kevlar 49	1420/968	18.2 ± 0.6	907.2 ± 4.3	2.2 ± 0.08
PEN-HM	1500/210	8.6 ± 0.13	214.1 ± 5.1	6.2 ± 0.3
PEN-LM	1500/300	8.3 ± 0.07	161.5 ± 7	11 ± 0.4
PEN-HT	1435/210	9.5 ± 0.2	215.4 ± 8.2	5.5 ± 0.1
PEN-SP special spin finish	1500/210	9.3 ± 0.2	221.9 ± 6	6.9 ± 0.7

of various fibers. Cunnif[38] investigated hybridization of armor systems by replacing the material at the strike face with a less expensive material. Larsson and Svensson[39] investigated hybrid composites containing carbon and polyethylene (Dyneema) fibers in rigid and flexible epoxy matrices. It was shown that the best ballistic protection was obtained with laminates consisting of two types of fibers separated so that the carbon fiber reinforced part was at the front of the laminates. Thomas[35] found that using a nonwoven facing on a woven fabric provided enhanced ballistic performance rather than just Spectra shield alone. Further improvement was found by using a Spectra shield facing on a nonwoven, backed by fabric. The use of layers of woven and nonwoven aramid textiles has also been studied by Chitrangad.[40] In this report, we made several hybrid samples from PEN with Kevlar 49 and Dyneema.

To the best of our knowledge, in this endeavor, we studied for the first time the ballistic performance of woven and nonwoven soft and composite armors made of PEN fibers. This study reviews the effect of tensile properties of PEN fibers on the ballistic performance of PEN materials in three categories: (a) woven and nonwoven soft armors; (b) woven and nonwoven hybrid soft armors; and (c) woven and nonwoven composite armors. The ballistic performance of PEN armors in each category was compared with Kevlar 49 armor as reference. The ballistic performance of both soft and composite hydroentangled PEN nonwoven was compared to the woven PEN armors. To predict the ballistic performance of PEN materials from tensile properties of the fibers, the Cunniff's equation was modified by eliminating elongation at break from the equation.

EXPERIMENTAL

Materials

The tensile properties of four types of poly(ethylene naphthalate) yarn and Kevlar 49 yarn are given in Table I. The PEN-HM has higher modulus and a lower elongation at break than PEN-LM. The PEN-HT has higher tenacity compared to PEN-HM and PEN-LM. The PEN with special spin finish (SP) has higher adhesion to rubber for tire cord application. The woven fabrics with warp and weft density 26 × 36 (1/in) were prepared using a Jacob Müller weaving machine.

We also used Dyneema shield (basis weight of 122 g/m^2) for hybrid samples.

Filsize 5375 and Philbind L-1000 from Philchem were used for sizing of PEN and Kevlar 49 yarns, respectively. The sizing machine made by Yamada Corp. Model YS-6 (Japan) was used for sizing the yarns.

Epoxy resin 205 (rigid epoxy resin) and hardener 206 from West System was applied to fabrics using squeegee. After coating layers of fabric with epoxy resin, the composite was subjected to 20,000 lb pressure over night to complete polymerization. Finally, a 20 × 20 inch sample was cut for the ballistic testing.

Poly(ethylene naphthalate) (high modulus) crimped staple fibers (7 denier, 2 inch length, 30 crimps per inch) were used for making the web. The following processes were used for preparing hydroentangled nonwoven fabric samples:

- Carding
- Cross-lapping
- Preneedling of web 50 g/m^2 at 125 rpm
- Placed four, five, and six layers of web together and needle punched at 400 rpm (2 up, 2 down), punch density of 8 punch/cm^2
- Hydroentanglement process: pressure profile (30, 200, 200, 220, 220 bar), cone-down nozzle, conveyor belt speed of 10 m/min, nozzle diameter of 130 micrometer, 1025 number of holes in a strip, nozzle density of 40 holes/inch, coefficient of discharge (c_d) of 0.62 and two times pass.

Measurements

Denier

Denier of PEN and Kevlar yarns were measured by weighing a predetermined yarn length of 90 m.

Tensile properties

Tensile properties of PEN and Kevlar yarns were measured on a MTS Sintech testing machine following ASTM D2256. The results were given in Table I. A gauge length of 3 inches and a constant cross-head speed of 12 inch/min were adopted. An average of 10

TABLE II
Mechanical Properties of PEN (High Modulus) Hydro-Entangled Nonwovens

No. of fabric layers	Basis weight (g/m^2)	Tenacity[a] (lbf)	Tenacity[b] (lbf)	Elongation at break[a] (%)	Elongation at break[b] (%)	Density (g/cm^3)	Thickness (mm)
Four layers	211.8 ± 3.8	97.4 ± 4.9	116 ± 3.4	78.4 ± 1.8	88.5 ± 3.9	0.124	1.7
Five layers	220.03 ± 3.8	106.5 ± 6.7	112.5 ± 4.8	72.9 ± 1.4	92.5 ± 3.9	0.128	1.72
Six layers	292.5 ± 11.6	139 ± 8.5	163.2 ± 7.9	80.8 ± 3.3	84 ± 2.4	0.139	2.1

[a] Machine direction.
[b] Cross-machine direction.

individual tensile determinations was reported for each sample.

Tensile properties of PEN nonwovens were measured by using an MTS (Sintech) testing machinefollowing ASTM D5034 (Table II). A gauge length of 3 inches and a cross-head speed of 12 inch/min were adopted. Size of samples was 4 × 6 inches. An average of five individual tensile determinations was reported for machine and cross directions.

Ballistic test (V50 velocity)

The National Institute of Justice (NIJ) standard test 0101.04 is one of the most widely used ballistic tests. This standard method establishes the minimum performance requirement and test method for the ballistic resistance of personal body armor for protecting the human torso against handgun and rifle gunfire. The standard also explains criteria for acceptance of the armor vest in terms of labeling, test sequence, labeling, tractability, and workmanship. In this standard, the ballistic resistance body armor is classified into different levels such as type I, IIA, II, and IIIA, which provide increasing levels of protection from handgun threats. Type III and IV armor, which is used mainly in tactical situations, protect against high powered rifle rounds. Generally, the number of protective layers in a vest could vary from 4 to 9 depending on the test classification.

NIJ standard test 0101.04 (Class I, .380 ACP) was used in this study for measuring V50 velocity. The average velocity of bullets was determined during tests by using two independent sets of chronographs. The V50 velocity is based on the average of equal numbers of velocities associated with complete penetration and partial penetration. Figure 1 shows the ballistic set-up and the first chronograph placed at the minimum of the 2 meter distance from the muzzle of the test barrel. The ballistic tests were conducted at H.P. White Laboratory, Maryland, USA.

RESULTS AND DISCUSSION

Woven PEN and Kevlar fabrics

The results of the ballistic tests on woven PEN and Kevlar 49 fabrics are given in Figure 2. As expected, Kevlar 49 fabrics had an exceptional ballistic performance and V50 of the armor made of 30 layers of PEN-HM (high modulus yarn) woven fabric was 42% lower than that one of Kevlar 49. Interestingly, 50 layers of PEN-HM produced nearly the same ballistic performance as 30 layers of Kevlar 49. In other words, the weight ratio of PEN-HM to Kevlar 49 should be at least 1.8 to achieve the same ballistic performance. This remarkable finding demonstrates that PEN yarns could be possibly used to produce armors.

As can be seen from Figure 2, V50 and ballistic limit (the lowest velocity for complete penetration) of PEN-HM fabrics were 32 and 84 ft/s, respectively, higher than those ones for PEN-LM fabrics. The investigation on the samples showed that the bullets

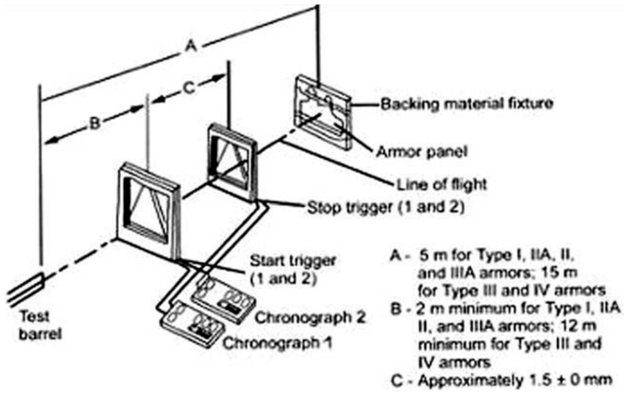

Figure 1 Ballistic test set-up.[28]

Set-up

Shot spacing:
PER MIL-STD-662F
Witness panel: Clay
Obliquity: 0 degree
Backing materials: 5.5″ Clay
Conditioning: Ambient

Range No.: 2
Temp.: 59 F
BP: 29.91 in.Hg
RH: 70%
Barrel No./Gun: TEST BARREL
Projectile: .380 ACP, 95 gr (6.2 g)

Primary Velocity Screens:
6.5 ft., 11.5 ft.
Primary Vel. Screen
Location: 9 ft. from muzzle
Residual Velocity
Screens: NA
Residual Vel. Location: NA
Range to target: 16.4 ft
Target to witness: 0 inch

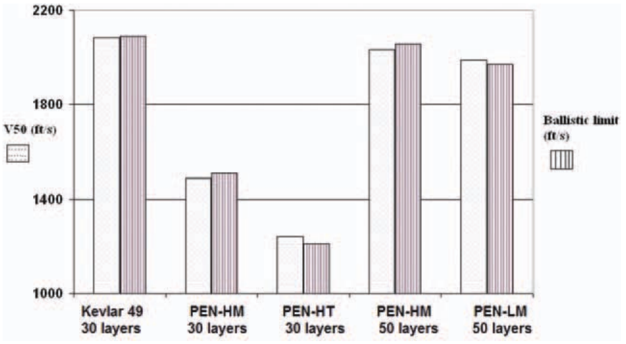

Figure 2 V50 and ballistic limit of PEN woven soft armor samples. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

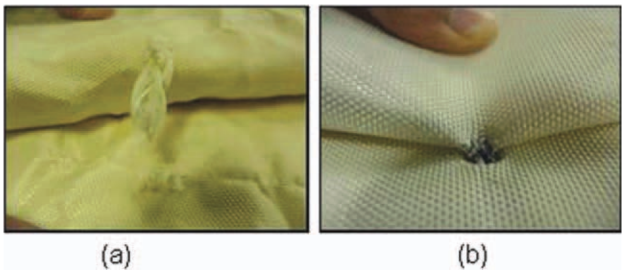

Figure 3 (a) Kevlar woven fabrics after ballistic test (pulling yarn) and (b) PEN woven fabric after ballistic test (the layers stick together). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

stopped in the PEN-HM samples three–four layers sooner than for PEN-LM. The higher ballistic limit of PEN-HM compared to PEN-LM indicates relatively higher ballistic resistance of PEN-HM. The sample made of high tenacity yarn (PEN-HT) showed a lower ballistic resistance compared to PEN-HM and PEN-LM samples. This low quality sample had many broken filaments and, therefore, exhibited a lower ballistic performance. This yarn sample was not used in any subsequent experiments. The KE absorbed by soft armor woven samples calculated based on eq. (2) is given in Table III illustrate the higher KE for PEN-HM compared to PEN-LM which is in agreement with the results of ballistic test.

The images of samples (Fig. 3) taken after performing the ballistic tests revealed interesting facts. One of the important issues was the melting of PEN fibers. The bullet could easily penetrate through PEN fabrics by melting the fibers. As we can observe from photos in Figure 3, the layers of PEN fabrics stick together due to melting of the fibers (T_m of PEN is around 267°C). Melt damage, the limitation of all thermoplastic polymeric fibers in ballistic application, was also reported for Spectra fibers (UHMWPE).[41] The size of the holes in the layers of Kevlar fabrics were smaller than those in the PEN samples. Furthermore, the bullet penetrated only through the outer layers of Kevlar sample after breaking the individual fibers. The photographs in Figure 4 also show fibrillation of Kevlar and melting of PEN fibers. Fibrillation contributes to energy absorption capacity and can further limit any subsequent fiber or yarn failure.

TABLE III
Kinetic Energy Absorption of Soft Armor Samples for Woven PEN and Kevlar 49 Fabrics

Sample type	Sample weight[a] (lbs)	Number of layers	Kinetic energy (J)
Kevlar 49	3.15	30	1252
PEN-HM	5.46	50	1189
PEN-LM	5.68	50	1150
PEN-HM	3.19	30	637
PEN-HT	3.06	30	444

[a] Weight of a 20 × 20 inch sample.

We used Cunniff's equation to predict the ballistic performance for various PEN and Kevlar fibers and to compare ballistic test results. The results of U^* from eq. (1) listed in Table IV, indicated that U^* increased with an increasing tenacity and modulus for different types of Kevlar yarns and it was in the good agreement with ballistic measurements. Actually, the Cunniff's equation works well for super high performance fibers such as Kevlar that have a very low elongation at break in the range from 3.6 to 4.4%. This is not case for our experimental fabrics made from PEN fibers with elongation varying from 8 to 18%. U^* calculated for the PEN yarn having a low modulus and a high elongation of 18% was the highest among yarns tested. In reality, one should expect just the opposite behavior. Indeed, measurements of V50 showed that the fabric made of the low modulus and the high elongation yarn had the lower ballistic resistance than that one for PEN-LM fabrics (see Fig. 2). When the elongation at break was removed from the Cunniff's equation or in other words we assumed that fibers had the

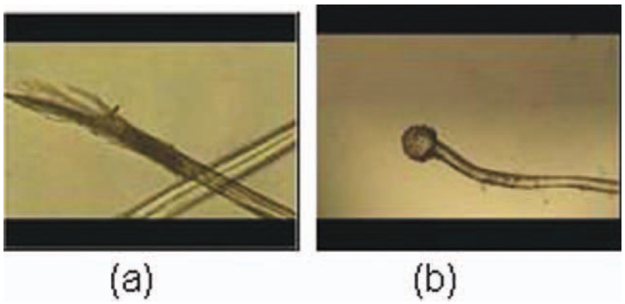

Figure 4 (a) Fibrillated Kevlar fiber after ballistic test and (b) melted PEN fiber after ballistic test. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE IV
Study of U^* and U^{**} for Different Types of Kevlar and PEN Fabrics

Fiber	Tenacity (GPa)	Modulus (GPa)	Elongation at break (%)	U^* (ft/s) Eq. 2	U^{**} (ft/s) Eq. 3	U^* ratio [Eq. (2)]		U^{**} ratio [Eq. (3)]		V50 ratio	
						$\left(\frac{U^*}{U^*_{\text{kelvar 292}}}\right)$	$\left(\frac{U^*}{U^*_{\text{PEN-HM}}}\right)$	$\left(\frac{U^{**}}{U^{**}_{\text{kelvar 292}}}\right)$	$\left(\frac{U^{**}}{U^{**}_{\text{PEN-HM}}}\right)$	$\left(\frac{V50}{V50_{\text{kelvar 292}}}\right)$	$\left(\frac{V50}{V50_{\text{PEN-HM}}}\right)$
Kevlar 119[43]	2.95	54.17	4.4	10085.3	6154.7	1.03		0.96		0.97	
Kevlar 129[44]	3.24	99	3.2	10229.5	6906.08	1.04		1.08		1.14	
Kevlar 292	2.87	78.8	3.6	9783.3	6381.1	1		1		1	
PEN-LM	1.05	18	18	9586.4	3658.09		1.11		0.97		0.98
PEN-HM	1.08	20.3	12	8628.5	3769.6		1		1		1
PEN-UHT	1.58	26	8	8917.2	4458.6		1.03		1.18		1.18
PEN-UHT (Goal)	2	30	5	8448.06	4940.8		0.88		1.31		1.31

same elongation (for example 1%), then U^{**} calculated from eq. (3) correlated well with V50 ratio for both PEN and Kevlar yarns (see Table IV).

$$U^{**1/3} = \left(\frac{\sigma}{2\rho}\right)\sqrt{\frac{E}{\rho}} \tag{3}$$

The Cunniff's equation implies that a higher fiber elongation should increase U^* and result in a higher ballistic performance. Obviously, this a little flaw. Yarns with high elongation at break are less oriented and consequently exhibit lower modulus and tenacity. To achieve the ballistic goal, the ultimate strain ε should be kept as low as possible. Therefore, assuming $\varepsilon = 1\%$ was the best choice to predict ballistic behavior of fabric produced from medium tenacity yarns.

Our work delivered the strongest ever PEN fibers with tenacity of 12.5 g/den (PEN-UHT) by a novel melt spinning process.[42] We believe that this value could be much higher. Therefore, we attempted to predict the ballistic performance of the PEN fibers spun by our process. The results in Table V illustrated that weight ratio of PEN-UHT to Kevlar 49 will decrease to 1.35 from 1.8 for commercial PEN yarn with 8.5 g/den tenacity. The calculations also demonstrated that by increasing tenacity of PEN fibers to 15.7 g/den (2 GPa), modulus 30 GPa, and elongation at break of 5%, the V50 would be 1.31 times higher than V50 of high modulus PEN soft armor sample.

Based on our ballistic tests and the relationship between weight of the sample (number of layers) and V50 for PEN fabrics (Table V), the weight ratio of PEN yarn with 15.7 g/den tenacity to Kevlar 49 would be just 1.13, or in other words 34 layers of PEN should have the same ballistic resistance as 30 layers of Kevlar 49 fabrics. It is important to mention that some other factors such as fiber morphology, higher PEN melting point, or compressive properties could change our prediction.

Nonwoven and hybrid samples

This part summarizes the ballistic performance of PEN nonwoven materials and different hybrid samples. The results of the ballistic tests in Table VI revealed that the hydroentangled nonwoven soft armor had a potential for absorption of KE of a bullet. However, as shown in Table VI, the nonwoven samples have a lower KE absorption than woven fabrics. Although it is important to mention, the latter fabrics had much higher basis weight. We believe that the ballistic performance of nonwoven soft armors can be improved by increasing the basis

TABLE V
Prediction of the Weight Ratio of PEN to Kevlar 49 Fabrics

Fiber	No. of layers	V50 (ft/s)	Increase in weight to reach V50 of 30 layers of Kevlar fabrics
PEN (HM)	30	1488	1.8
PEN (HM)	50	2055	1
PEN (UHT)	30	1.18 × 1488 = 1756	
PEN (Goal)	30	1.31 × 1488 = 1949	
PEN (Goal)	34	2085	1.13

weight of the nonwoven web layer and fiber entanglements in the hydroentanglement process. Figure 5(a,b) show damage to PEN nonwoven and woven samples after ballistic test, respectively.

In other part of this study, we also evaluated the ballistic performance of hybrid samples. The results of hybrid samples of PEN/Kevlar 49 showed that by using 10 layers of Kevlar 49 at the back face of the sample, the V50 improved 10% compared to 30 layers of PEN-HM fabric.

The results in Table VI and Figure 6 show that V50 of the hybrid sample of PEN/Dyneema decreased by 90 ft/s (∼ 6%) compared to the PEN-HM sample. Observations of samples after ballistic test showed buckling (large deformation around the impact point) at layers bullet did not penetrate, and breaking of Dyneema fibers after penetration of the bullet. Attention must be paid to the weakest point of Dyneema in ballistic armors application which is its low melting point of 150°C. The ballistic tests revealed that Dyneema shield (at the back face) does not improve the ballistic performance of the hybrid soft armor made from PEN/Dyneema. Dyneema fibers have an excellent high tensile strength (35–42 g/den), toughness, cutting resistance, but low compressive and flexural strength. This makes them unsuitable for a number of composite applications. Dyneema shows poor adhesion to composite matrix systems because of its inert chemical composition which would reduce the composite compressive strength.

Chitrangad[44] has proposed using weft yarns having a higher elongation to break to improve ballistic performance. He reasoned that because the weft yarns possess less crimp, they would break before the warp yarns, because warp yarns need more time to decrimp and then elongate to failure. The results of the V50 test in Figure 6 revealed that by using PEN-LM as weft in woven fabric, the ballistic resistance decreased 22.8% compared to that of PEN-HM fabric at the same number of layers of 30. Therefore, our results demonstrate that the theory of using high elongation at break of weft yarns may not be valid. However, we might conclude that the low modulus and higher elongation weft yarns broke easier during deflection of secondary yarns.

The hybrid soft armor composed of 74 wt % woven and 26% nonwoven had 7.8% decrease in weight compared to 30 layers of PEN-HM woven fabric and a 18% decrease in V50. The hybrid woven and nonwoven sample with 7.8% lower weight had higher ballistic performance compared to the hybrid woven sample made from warp PEN-HM and weft PEN-LM. The hybrid woven sample with PEN-LM in weft showed 22.8% decrease in V50 compared to PEN-HM woven fabric. This comparison between hybrid woven and nonwoven and hybrid woven PEN-HM in warp and PEN-LM in weft prove that the nonwoven layers at the face of samples showed higher global energy absorption compared to the woven fabric. Therefore, this reasoning indicates the potential application of PEN nonwoven in ballistic applications. The calculated KE absorption by hybrid samples given in Table VI showed higher KE in woven/nonwoven hybrid sample than hybrid woven fabric with PEN-LM in weft which confirms the results of the ballistic tests.

Composite samples

The Figure 7 demonstrates that the V50 velocity for all woven fabrics composed of PEN and Kevlar is lower than their soft armors. The composite sample of low modulus PEN-LM had a 35% higher V50 than the composite high modulus PEN-HM sample.

TABLE VI
The Kinetic Energy Absorbed by Nonwoven and Hybrid Samples

Sample type	Sample weight[a] (lbs)	Number of fabric layers	Kinetic energy (J)
Woven PEN-HM	3.19	30	637
PEN-HM + Kevlar 49 hybrid	3.21	20 + 10	774
Woven PEN–HM + PEN-LM	3.35 (42% HM)	30	380
PEN-HM + Dyneema hybrid	3.96	25 + 5	563
Nonwoven PEN-HM	2.25	50	242
Nonwoven PEN-HM	1.34	30	177
Woven PEN-HM + Nonwoven PEN-HM	2.94 (26 wt % nonwoven)	20 + 14	423

[a] Weight of a 20 × 20 inch sample.

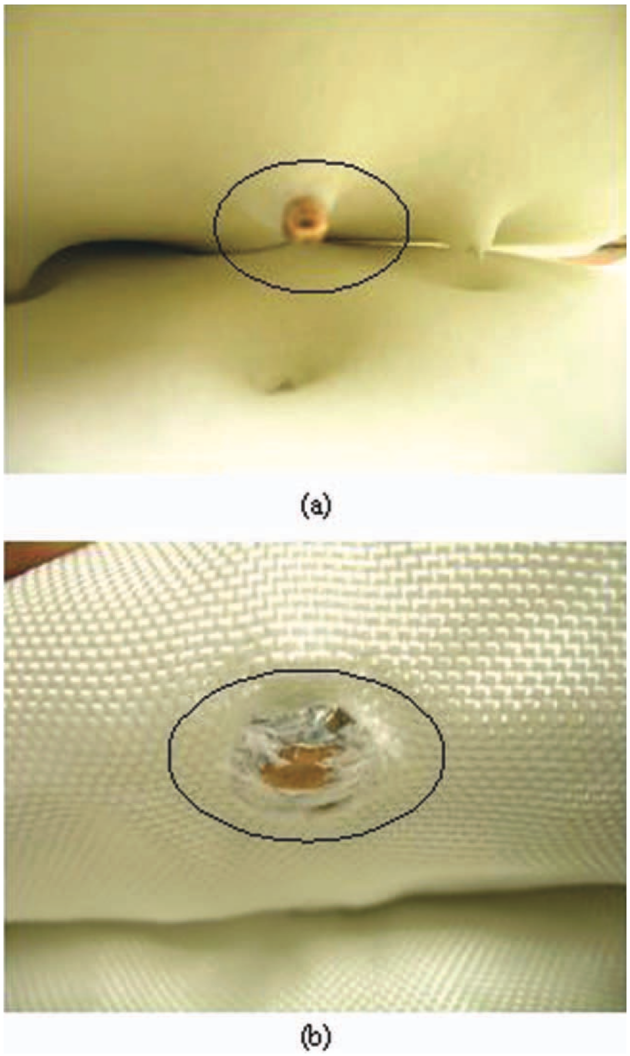

Figure 5 (a) PEN nonwoven sample after ballistic test and (b) PEN woven fabric after ballistic test. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

This could be because of: (a) higher adhesion of epoxy resin to PEN-LM; (b) lower delamination of PEN-LM; (c) lower shear plugging due to global energy absorption as a result of the higher toughness of lower modulus and higher elongation of low modulus PEN-LM. By using high modulus PEN-HM (SP) with a special SP, which provides higher adhesion, the V50 velocity increased 49 ft/s compared to PEN-HM. The main factor in higher ballistic resistance in low modulus PEN yarn is due to the mechanical properties which affect energy absorption of the composite. The interesting result is that V50 of the nonwoven composite sample is 37% higher than that of the soft nonwoven armor which is a completely different trend compared to woven samples. The nonwoven composite sample did not show a high degree of delamination after the ballistic test. The reason for the increase in V50 in the nonwoven composite could be due to high interfacial adhesion between fibers and resin in the nonwoven as a result of high surface area between them, and the epoxy resin in the overall absorption of KE of the bullet. This result promises potential application for nonwoven composites in automotive, transport, and construction applications. The calculated KE absorption by composite samples is given in Table VII and showed the highest KE for Kevlar 49 and then PEN-LM in second place.

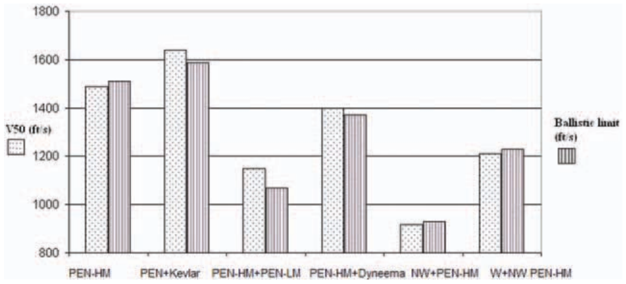

Figure 6 V50 and ballistic limit of hybrid samples. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

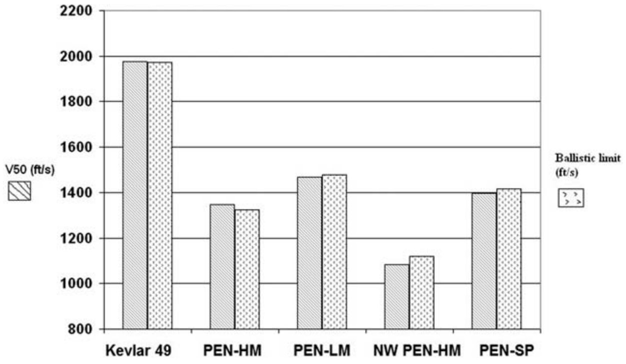

Figure 7 V50 and ballistic limit of woven and nonwoven composite samples.

Summary

The comparison of ballistic performance and mechanism of energy absorption of different types of armors based on the physical properties of PEN fibers which was discussed in above sections is summarized in the Table VIII. The major factors that

TABLE VII
The Kinetic Energy Absorbed by Composite Samples

Sample type	Weight (lbs)	Number of layers	Kinetic energy (J)
Kevlar 49	2.61	30	1126
PEN-HM	2.72	30	523
PEN-LM	2.91	30	620
Nonwoven PEN-HM	2.45	30	339
PEN-SP	2.76	30	562

TABLE VIII
Comparison of Ballistic Performance of Different Types of PEN Armors

Structure of PEN armor (30 layers)		V50 Velocity (ft/s)	Kinetic energy absorbed by armor (J)	Ballistic performance mechanism
Woven-soft	PEN-HM	1488	637	Weight ratio of PEN to Kevlar 49 of 1.8 at same ballistic performance
	PEN-LM	1456	610	Melting PEN and fibrillation of Kevlar fibers HM has a higher ballistic performance than LM
Woven-composite	PEN-HM	1348	523	Woven composite has a lower ballistic performance than soft
	PEN-LM	1467	620	LM has a higher ballistic performance than HM which is opposite for the soft armor behavior probably due to higher toughness of PEN-LM
Hybrid	Woven PEN-HM + PEN-LM	1149	380	LM yarns in weft reduced ballistic performance of woven fabric
	Nonwoven PEN-HM + Woven PEN-HM	1212	423	A lower ballistic performance than woven HM Nonwoven showed more global energy absorption than woven armor
Nonwoven-soft	PEN-HM	614	177	Nonwoven had a lower ballistic performance than woven armor Need more compact structure for nonwoven
Nonwoven-composite	PEN-HM	1085	339	Nonwoven composite has a higher ballistic performance than nonwoven soft Nonwoven composite didn't show delamination Higher interfacial adhesion in nonwoven

HM, high modulus; LM, low modulus.

affect the ballistic performance mechanisms of PEN armors can be listed as follows:

- The weight ratio of PEN-HM to Kevlar 49 should be at least 1.8 to achieve the same ballistic performance. This remarkable finding demonstrates that PEN yarns could be possibly used to produce armors.
- Melting PEN and fibrillation of Kevlar fibers occurs during ballistic test.
- Nonwoven showed more global energy absorption than woven armors.
- LM has higher ballistic performance than HM armor which is the opposite of soft armor behavior probably due to higher toughness of PEN-LM.

CONCLUSIONS

In this endeavor, the ballistic performance of PEN woven and nonwoven soft and composite armors was investigated and compared to Kevlar 49 as a reference. The core objective of this work, as part of our research for improving the tensile properties of PEN fibers, was to study the effect of modulus and tenacity of PEN yarns on the ballistic performance of woven fabric. The Cunniff's equation revised by eliminating elongation at break showed good agreement with the ballistic results for PEN samples. The results of our calculations showed that by increasing tenacity of PEN yarn from 8.5 g /den (commercial) to 12.5 g/den (produced by our research group), the weight ratio of PEN to Kevlar 49 decreased from 1.8 to 1.35 for the same ballistic performance.

The hybrid soft armor made of woven and nonwoven PEN revealed higher ballistic resistance compared to woven fabric made of high modulus PEN yarns as warp and low modulus PEN as weft. The hydroentangled PEN nonwoven had a higher potential for absorbing the KE of the bullet.

In the composite armors, contrary to the results of the soft armors, the low modulus PEN had 17% higher V50 than high modulus PEN. The nonwoven composite armor indicated a higher ballistic performance than nonwoven soft armor. However, PEN and Kevlar woven composite armors showed a lower ballistic performance compared to their soft woven armors. The results of our ballistic tests demonstrated that high tenacity PEN fibers, which were produced by our research group, have potential application in soft and composite armors, high velocity impact applications, and improve performance of PEN products in current applications such as tire, belt, or reinforced composites.

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