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Nylon-Coated Ultra High Molecular Weight Polyethylene Fabric for Enhanced Penetration Resistance

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ABSTRACT: A coating of Nylon 6,6 or 6,12 was used to improve the penetration resistance of ultra high molecular weight polyethylene (UHMWPE) fabric that would be potentially useful in the manufacture of flexible body armor against spike/knife threats. Quasi-static test results for the spike penetrator showed a 77% and 86% improvement in the puncture resistance of Nylon 6,6 and Nylon 6,12 coated UHMWPE (respectively) over a neat fabric target of equivalent areal densities. Dynamic impact testing demonstrated dramatic improvement in the puncture resistance of nylon-coated fabrics while only a slight improvement in stab resistance was observed comparing samples with equivalent areal densities. Photography of ruptured areas after quasi-static testing revealed limited fiber motion or fiber stretching with no evidence of fiber pullout for nylon-coated fabric samples in contrast to neat fabric. This suggests that there was a significant increase in energy absorption by nylon-coated fabrics at impact. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2014**, *131*, 40350.

KEYWORDS: coatings; polyimides; fibers; textiles; applications

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INTRODUCTION

Stab and puncture resistant materials have become increasingly more important in light of the higher incidence of knife assaults in urban and military conflicts. Generally, providing good puncture and stab resistance with body armor is more difficult to achieve than ballistic resistance.[1–11] Development of lightweight, high strength, and high modulus fibers has introduced a new era of soft body armor materials that has obsoleted conventional forms of protection.[12–15] Typically, high strength fibers (e.g., Kevlar®, Spectra®, and Dyneema®) are used in the manufacture of fabric-based body armor to provide ballistic resistance, as these fibers possess high strength, high energy absorption, and lightweight properties.[10,16,17] However, they do not meet the standards against stab attacks.[1,2,6,10] More recently, ultra high molecular weight polyethylene (UHMWPE) has received considerable attention by several protection industries. The light weight, high strength, high elastic modulus, excellent chemical resistance, and low moisture absorption properties of UHMWPE make it an ideal alternative to other reinforced fibers, such as Kevlar.[11,13,18–20]

Previous studies have investigated the improvement in ballistic/puncture resistance of high strength fabrics impregnated with shear thickening fluid (STF), also known as liquid body armor technology although the cut resistance was not changed significantly.[1–4,8,9,14–17,21–27] A significant drawback with the use of this technology is that STFs can lose their unique rheological properties with aging or exposure to moisture.[8] In addition, UHMWPE, unlike Kevlar, is inherently inert with a low surface energy and a smooth fiber surface [13,18,28–30] that often results in poor interaction with other materials such as STFs. In the present study, Nylon 6,6 and 6,12 coatings to increase the performance and penetration resistance of UHMWPE fabric were investigated,[31] using quasi-static and dynamic impact testing and discussed below.

MATERIALS AND EXPERIMENTAL DETAILS

Materials

Nylon 6,6 ($C_{12}H_{26}N_2O_2$, $\rho = 1.14$ g mL^{-1}) and 6,12 ($C_{18}H_{34}O_2N_2$, $\rho = 1.13$ g mL^{-1}) pellets (Sigma Aldrich, Canada) were used to coat UHMWPE fabric samples. Anhydrous methyl (MeOH) and ethyl (EtOH) alcohol and ASC grade anhydrous calcium chloride, $CaCl_2$ (VWR, Canada) were used to dissolve nylon pellets. The UHMWPE plain woven fabric with an areal density of 231 g m^{-2} and 21 × 21 yarns per inch were supplied by Barrday, Canada.

Nylon Coating Preparation

Nylon 6,6 and 6,12 pellets were dissolved in anhydrous MeOH and EtOH, respectively, in the presence of anhydrous $CaCl_2$.

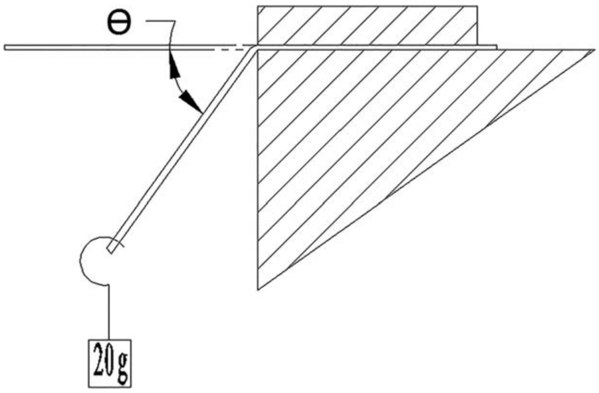

Figure 1. Schematic of flexibility test setup.

The ratio of nylon to $CaCl_2$ to alcohol in solution was most preferably 1 : 5 : 21 (by weight). The solution was heated to the reflux temperature of the alcohol for several hours to completely dissolve the nylon pellets. Plain-woven UHMWPE fabric was cut to the desired size and then submerged in the nylon/alcohol solution for 30 s. A manual rubber-coated nip roller was used to squeeze out excess nylon solution from the fabric and ensure a reasonable uniform coated fabric sample. The coated fabric samples were hung for several hours and then rinsed in distilled water for 5 min to remove residual $CaCl_2$. The wet fabric samples were then hung overnight in the fume hood to dry completely prior to testing.

Flexibility Test, Measurements, SEM, and DSC

Flexibility test and thickness measurement were done to examine the impact of the nylon-coated UHMWPE samples to neat UHMWPE fabric. To perform the flexibility test, [16,21] coated and neat UHMWPE fabric were cut to 5 cm × 10 cm pieces and sealed tightly in polyethylene bags using a manual impulse sealer. The sample was then held firmly at the edge of a hard piece of wood with 3.8 cm of the length of the sample exposed. A 20 g weight was attached to the end of the sample [Figure 1] and the bending angle (BA) of the fabric measured with a protractor. The thickness and weight of all UHMWPE fabric samples were measured before and after the nylon coating was applied. Scanning electron microscopy (SEM) study was carried out using a JEOL 6380LV scanning electron microscope to analyze the morphological characteristics of the samples. The melting points of as received nylon pellets and converted nylon coating were measured using a Perkin-Elmer Pyris diamond differential scanning calorimeter at a scan rate of 10 K min^{-1}. To prepare the nylon coating, nylon pellets were dissolved in the same refluxing system mentioned in section "Nylon Coating Preparation". A small amount of the solution was then dropped on a wide plate and left under a vacuum chamber for 2 days ensuring that the alcohol evaporated completely. The thin, nylon membrane-like coating was then immersed in distilled water for 1 h to remove $CaCl_2$ and placed under vacuum for overnight to dry.

Dynamic Impact Test

A drop mass weapon and backing materials were prepared using a modification of the NIJ Standard 0115.00. The combination of backing materials comprised four layers of 6.3 mm thick neoprene sponge, followed by one layer of 22 mm thick polyethylene foam followed by two layers of 6 mm thick dense rubber. Five layers of very thin tracing papers (as tear-proof witness papers) were then placed on top, bottom, and between the layers of neoprene sponges to determine the relative depth of penetration (Table I). This procedure differed from the current NIJ protocols which suggests to place a single witness paper on the backing material to determine the depth of penetration by measuring the dimension of the paper cut. The reason for the deviation was to provide an easier and more accurate measurement of the depth of penetration.[10] The upper part of the drop mass was machined from a Nylon 6 rod and it includes the appropriate polyethylene foam discs as dampers. The bottom part of the drop mass is comprised of a carbon steel pipe attached to a stainless steel weapon [Figure 2]. Three different types of threat weapons were machined according to the NIJ Standard 0115.00 [Figure 3]: spike (pointed weapon), S1, and P1 (edged blades) each of which weighed 450 g. The complete assembly of the drop mass was 2268 g (including the threat weapon). The drop mass was freely released from two different arbitrary heights in a polyvinyl chloride (PVC) pipe attached and fixed to a hard block wall with steel channels. The velocity of the impactor just prior to the impact was recorded with a high-speed camera (MotionPro X3) to calculate the actual impact energy. The impact energies were calculated to 1.1 and 2.5 Jusing the recorded impact velocities and total mass of the drop weapon. The impact test was conducted in such a manner as to provide a reasonable comparison between our samples in the matter of the penetration resistance comparable to similar experiments. [1,32,33] In contrast, the NIJ standard suggests different impact energies to evaluate the penetration resistance of the

Table I. Relative Depth of Penetration.

Number of ruptured witness paper(s)	Approximate penetration depth (mm)
0	0
1	0–6.3
2	6.3–12.6
3	12.6–18.9
4	18.9–25.2
5	>25.2

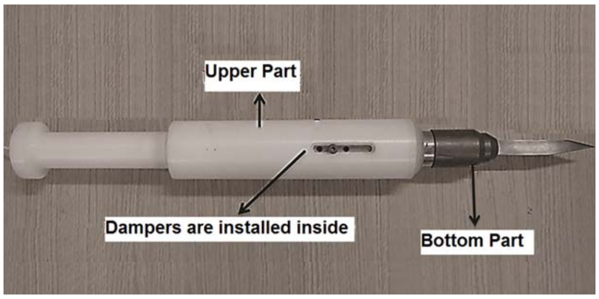

Figure 2. Drop mass weapon used for the dynamic impact test. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 3. Weapons used: (a) P1 blade, (b) Spike, and (c) S1 blade. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

final manufactured panel of body armor vest including dozens of fabric layers. The impact energies and the number of ruptured witness papers were used to compare the penetration resistance of neat and coated UHMWPE fabric samples. Two stacked layers of Nylon 6,6 and two layers of Nylon 6,12 coated UHMWPE fabric samples were compared individually to three layers of neat UHMWPE fabric sample of equivalent areal densities. Each test was performed in triplicate for each sample (sealed in polyethylene bags using a manual impulse sealer) and each weapon type to confirm the reproducibility. The penetration depths were reported by inspecting the number of damaged witness papers.

Quasi-Static Test

Quasi-static tests were performed to study the mechanism of stab/puncture attacks on penetration resistance of nylon-coated UHMWPE fabric samples and to explore the evolution and phenomenology of failure using a TestResources tensile testing machine (TestResources, MN) with 5 KN load cell. The NIJ standard weapons (spike, S1, and P1) mounted to the upper grip of the machine were driven through the 15 cm × 15 cm testing target at 5 mm/min for 35 mm.[11,16] The test fixture was machined according to the ASTM D4833-00E1. The target fabric was fixed between two concentric plates by careful tightening of three bar clamps to avoid any induced tension. A coarse sandpaper was bonded to the opposing surface of the circular plates to prevent fabric slippage. The load cell with specific quasi-static test fixtures is shown in Figure 4. Two layers of Nylon 6,6 and two layers of Nylon 6,12 coated UHMWPE fabric samples were compared individually to three layers of neat UHMWPE fabric sample of equivalent areal densities similar to the testing as discussed in section "Dynamic Impact Test."

To assess the effect of moisture absorption on the penetration resistance of both neat and nylon-coated UHMWPE fabrics, two different test conditions were applied to one layer fabric samples prior to testing. The first set of samples were dried in a vacuum chamber and stored in sealed polyethylene bags and the second set of samples were fully immersed in distilled water for 24 h. Tests were performed 5 times in all cases to confirm the reproducibility. From the quasi-static graphs, total puncture/stab energy dissipation by the fabric samples was also calculated by integrating the load-displacement curves. After each test at dry condition, the samples were photographed on the front side to study the mechanisms of damage.

RESULTS AND DISCUSSION

Nylon-Coated UHMWPE Fabrics

Table II lists the areal density, BA, and thickness of neat and nylon-coated UHMWPE fabrics of different number of layers. The BA correlates with the flexibility of the sample; as the flexibility of the sample increases, the BA also increases. From Table II, it was shown that one layer of neat UHMWPE fabric sample ($BA = 61 \pm 2°$) was slightly more flexible than one layer of Nylon 6,6 and Nylon 6,12 coated UHMWPE fabric samples ($54 \pm 2°$ and $55 \pm 2°$, respectively). Although, two layers of Nylon 6,6 coated UHMWPE fabric ($BA = 43 \pm 2°$) and two layers of Nylon 6,12 coated UHMWPE fabric ($BA = 45 \pm 2°$) were more flexible than three layers of neat UHMWPE fabric ($BA = 35 \pm 1°$) of the equivalent areal densities. In addition, two layers of Nylon 6,6 and two layers of Nylon 6,12 coated

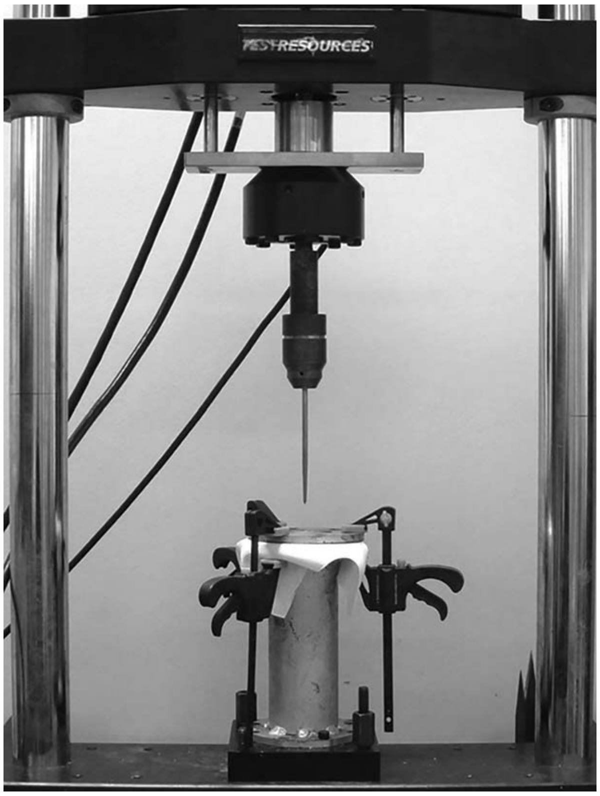

Figure 4. Quasi-static test setup.

Table II. Flexibility Test Results.

UHMWPE	Areal density ($\times 10^{-6}$ g cm^{-2})	BA (θ)	Thickness (mm)
1 layer neat	231 ± 1	61 ± 2°	0.43
1 layers Nylon 6,6 coated	323 ± 8	54 ± 2°	0.47
1 layer Nylon 6,12 coated	323 ± 8	55 ± 2°	0.48
3 layers neat	693 ± 1	35 ± 1°	1.26
2 layers Nylon 6,6 coated	658 ± 17	43 ± 2°	0.94
2 layers Nylon 6,12 coated	658 ± 17	45 ± 2°	0.96

fabric samples were 34% and 31% thinner (respectively) compared to three layers of neat UHMWPE fabric sample of equivalent areal densities. Scanning electron images for neat and nylon-coated fabric samples are shown in Figures 5 and 6 for top and cross-section views, respectively. From Figure 5(a,b), it was observed that Nylon 6,6 coating penetrated and dispersed throughout the UHMWPE fabric filling all spaces between the filaments. From Figure 5(c), similar penetratetion and disperstion were observed for Nylon 6,12 coated fabric sample.

Impact of $CaCl_2$ on Nylon Coating

$CaCl_2$ forms a complex compound with nylon by breaking hydrogen bonds between the nylon molecules and reducing the intermolecular interactions of the nylon polymer. The alcohol facilitated the complexation of $CaCl_2$ with nylon,[34] and it helps to dissolve the nylon solution into individual fibers. After coating, drying, and washing, some percentage of the hydrogen bonding is restored within the system as the residual $CaCl_2$ precipitates out of the coating with the wash water. Different weight fractions of the constituents in the reflux system were examined to explore the optimum one which was found out to be 1 : 5 : 21 (nylon : $CaCl_2$: alcohol). It was observed that a lower concentration of $CaCl_2$ in the solution results in the incomplete solution of nylon pellets. Another problem with an insufficient percentage of $CaCl_2$ is that the solution of nylon/$CaCl_2$/alcohol did not remain soluble when cooled down to the room temperature and had to be reheated. In addition, the results from a differential scanning calorimetry (DSC) analysis of virgin nylon pellets and the washed nylon coating indicated that there was no change in the melting temperature.

The SEM images in Figuer 6 revealed that the filaments were close packed in the case of nylon-coated fabric samples but were loose in the neat fabric sample. This close packing was a result of mechanical interlocking of nylon coating onto the filaments which was due to the shrinkage of nylon after removal of $CaCl_2$ by water washing. It was also observed from Figure 6 that the filaments were more compact in the case of Nylon 6,12 compared to the Nylon 6,6 coated fabric. This could be interpreted as a mechanical interlocking of Nylon 6,12 around the UHMWPE fiber upon removal of $CaCl_2$ by water washing as more hydrogen bonds were restored and the spaces between the molecular chains were reduced.

Quasi-Static and Dynamic Tests

Figure 7 represents the quasi-static test results of the spike penetrator. It was shown that two layers of Nylon 6,6 coated UHMWPE fabric sample and two layers of Nylon 6,12 coated UHMWPE fabric sample (individually) provide a 77% and 86% improvement to the maximum resistance force in comparison with three stacked layers of neat UHMWPE fabric sample of equivalent areal densitiy. In all three samples, the maximum resistance peak occurred around 8–9 mm of penetration through the target. After the peak, the load dropped suddenly where the spike's tip was driven completely through the fabric target. The pushed-aside filaments adjacent to the penetrator continued to exert force on the spike which increased the load afterward. This load increase is due to the presence of frictional force between the failed filaments and the penetrator. In addition, the energy absorption values (Table III) of up to 35 mm of penetration (work done in the quasi-static test by the spike penetrator) by three layers of neat UHMWPE fabric sample, two layers of Nylon 6,6 coated UHMWPE fabric sample, and two layers of Nylon 6,12 coated UHMWPE fabric sample were 295×10^{-3}, 455×10^{-3}, and 427×10^{-3} J (respectively).

Figure 8 represents the quasi-static test results of the S1 blade penetrator. It was shown that two layers of Nylon 6,6 coated UHMWPE fabric sample and two layers of Nylon 6,12 coated UHMWPE fabric sample (individually) provided a slight improvement in cut resistance compared to three layers of neat UHMWPE fabric sample of equivalent areal densities. This improvement is more noticeable up to about 20 mm of penetration. Further resistance after this point is less important as the vital organs of the body could be damaged seriously by the

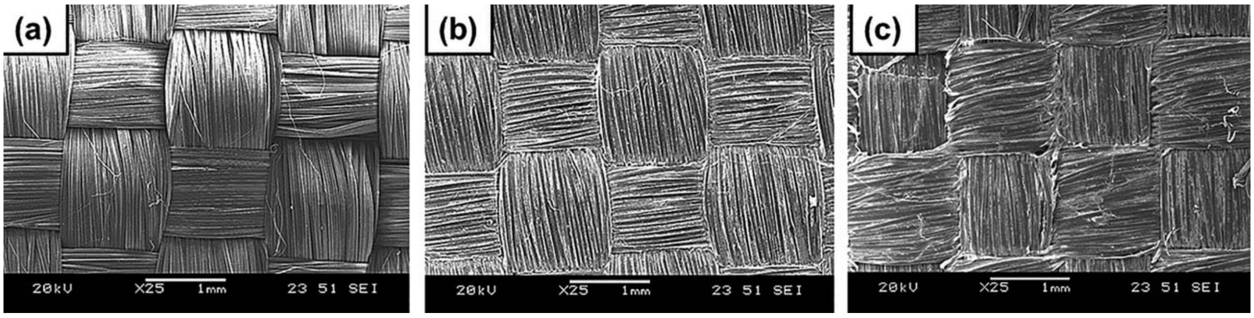

Figure 5. (a) Neat UHMWPE fabric, (b) Nylon 6,6 coated UHMWPE fabric, and (c) Nylon 6,12 coated UHMWPE fabric.

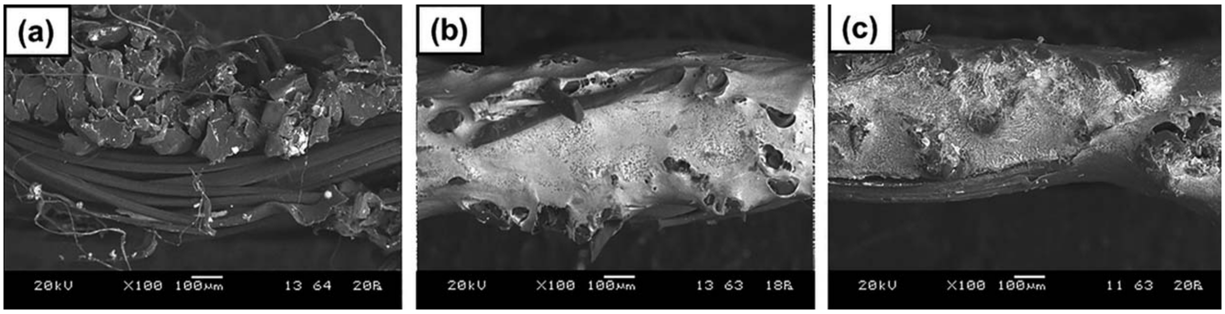

Figure 6. Cross-section view: (a) neat UHMWPE fabric, (b) Nylon 6,6 coated UHMWPE fabric, and (c) Nylon 6,12 coated UHMWPE fabric.

threat weapons according to the NIJ Standard 0115.00. The energy absorption values (Table III) of up to 35 mm of penetration (work done in the quasi-static test by the S1 penetrator) by three layers of neat UHMWPE fabric sample, two layers of Nylon 6,6 coated UHMWPE fabric sample, and two layers of Nylon 6,12 coated UHMWPE fabric sample were 937×10^{-3}, 975×10^{-3}, and 992×10^{-3} J (respectively).

Figure 9 represents the quasi-static test results of the P1 blade penetrator. From the results, it was shown that two layers of Nylon 6,6 coated UHMWPE fabric sample and two layers of Nylon 6,12 coated UHMWPE fabric sample (individually) provided the same cut resistance compared to three layers of neat UHMWPE fabric sample of equivalent areal densities, although, a slight improvement was noticed up to 10 mm of penetration of P1 blade. The energy absorption values (Table III) up to 35 mm of penetration (work done in the quasi-static test by the S1 penetrator) by three layers of neat UHMWPE fabric sample, two layers of Nylon 6,6 coated UHMWPE fabric sample were 580×10^{-3}, 603×10^{-3}, and 550×10^{-3} J (respectively).

It was shown by Figures 8 and 9 that the amplitude of oscillation for graphs of neat and nylon-coated fabric samples were large and irregular in the case of S1 and P1 blades which may correspond to the cutting or motion of several bunches of filaments at the same time.

Moreover, the energy absorption values for single layer samples of neat and nylon-coated UHMWPE fabric are presented in Table IV. It is observed that one layer of nylon-coated sample provides superior resistance against all three weapons compared to the neat fabric sample. The effect of moisture sensitivity of single layer samples of neat and nylon-coated UHMWPE fabric was also evaluated. According to the calculated energy absorption values shown in Table IV, there was no significant change in the quasi-static test results for nylon-coated samples under the two different test conditions (as mentioned in section "Quasi-Static Test"). It was also confirmed that there was no irreversible weight gain by neat or nylon-coated fabric samples immersed in water. Moreover, we observed that increasing the weight fraction of $CaCl_2$ in the refluxing system did not positively impact the results of the penetration tests.

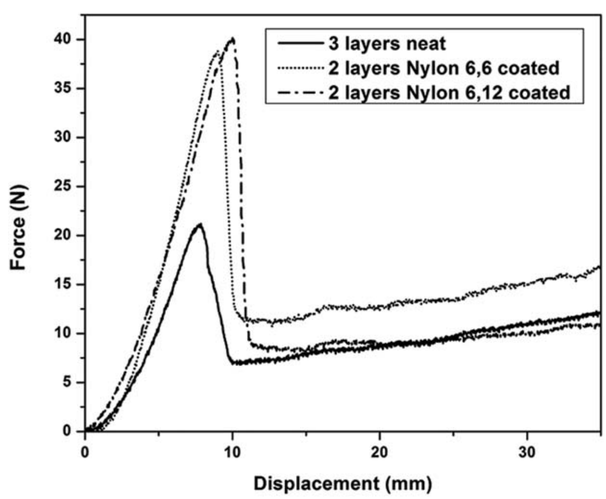

Figure 7. Quasi-static test results using a spike.

The results from the impact test are shown in Table V. Again, two layers of Nylon 6,6 coated UHMWPE fabric sample and two layers of Nylon 6,12 coated UHMWPE fabric sample were compared individually to three layers of neat UHMWPE fabric sample of equivalent areal densities. At the energy level of 1.1 J for neat fabric sample, the spike penetrated through two layers of neoprene sponges (three ruptured witness papers) which was equal to the approximate penetration depth of 12.6–18.9 mm (considering the thickness of neoprene sponges). Although at the same energy level, only one witness paper was ruptured for Nylon 6,6 or 6,12 coated samples (approximate depth of 0–6.3 mm). At the energy level of 2.5 J, the approximate depth of penetration was increased to 18.9–25.2 mm (four damaged witness papers) for neat fabric sample compared to 6.3–12.6 mm penetration (two damaged witness papers) for Nylon 6,6 or Nylon 6,12 coated fabric samples. For the P1 threat weapon, the penetration depth of neat fabric sample was 18.9–25.2 mm at 1.1 J and 2.5 J compared to 12.6–18.9 mm at 1.1 J and 18.9–25.2 mm at 2.5 J for Nylon 6,6 or Nylon 6,12 coated fabric

Table III. Energy Dissipation in Quasi-Static Test.

	The energy absorbed by fabric samples ($\times 10^{-3}$ J)		
UHMWPE	Spike	S1 blade	P1 blade
3 layers neat	295 ± 27	937 ± 83	580 ± 21
2 layers of Nylon 6,6 coated	455 ± 37	975 ± 75	603 ± 12
2 layers of Nylon 6,12 coated	427 ± 23	992 ± 85	550 ± 31

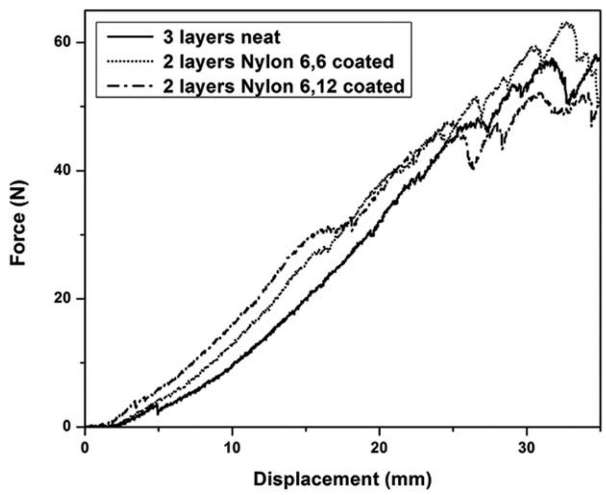

Figure 8. Quasi-static test results using an S1 blade.

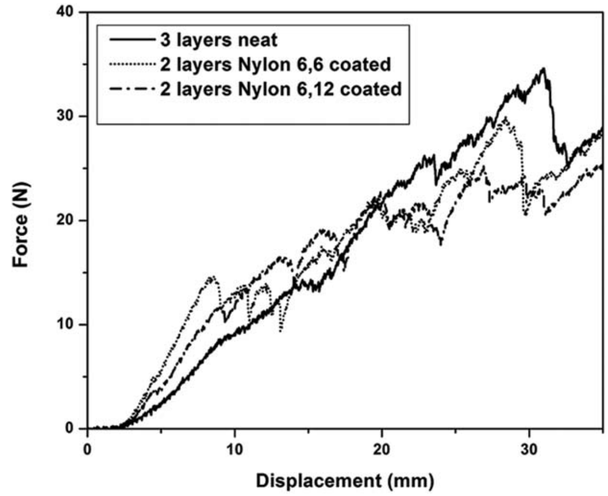

Figure 9. Quasi-static test results using a P1 blade.

samples. For the S1 threat weapon, the penetration depth of neat fabric sample was 12.6–18.9 mm at 1.1 J and 18.9–25.2 mm at 2.5 J compared to 6.3–12.6 mm at 1.1 J and 12.6–18.9 mm at 2.5 J for Nylon 6,6 or Nylon 6,12 coated fabric samples.

It was also noticed that the dynamic test results are in good agreement with the quasi-static test results demonstrating greater spike resistance of nylon-coated samples compared to the neat sample (with similar areal densities). Moreover, although the quasi-static graphs for S1 and P1 threats demonstrated better resistance of nylon-coated fabrics at the early stage of penetration, it also showed close energy absorption values for both neat and nylon-coated samples (2 vs. 3 layers with similar areal densities). In contrast, dynamic test results showed slightly better resistance of nylon-coated samples against the S1 blade at the energy level of 2.5 J while both neat and coated samples performed similarly against the P1 blade.

Fabric Damage Mechanism

It was observed that the evidence for fiber motion (pushing aside), and fiber pullout was more considerable in the case of neat UHMWPE fabric sample against a spike threat in comparison with nylon-coated UHMWPE fabric samples, shown in Figures 10(a), 11(a), and 12(a). This suggests that the point penetrator separated the filaments or fibers more easily (by pushing them to the sides) in the case of neat fabric sample which resulted in less penetration resistance. It was also concluded that a larger area of the fabric was involved in the case of nylon-coated samples because of the increase in interfilament friction or penetrator-fabric friction which decreased the mobility of the fiber and thereby increased the force required for the penetration. It was interpreted that although the windowing effect is dominant in puncture penetration, it is less significant for nylon-coated samples compared to the neat sample.

Table IV. Energy Dissipation in Quasi-Static Test (1 Layer Samples).

	The energy absorbed by fabric samples ($\times 10^{-3}$ J)					
	Spike		S1 blade		P1 blade	
UHMWPE	Dry	Wet	Dry	Wet	Dry	Wet
1 layer neat	73 ± 07	66 ± 06	405 ± 15	325 ± ± 24	199 ± 15	176 ± 15
1 layer of Nylon 6,6 coated	211 ± 23	198 ± 14	692 ± 25	676 ± 25	292 ± 22	280 ± 16
1 layer of Nylon 6,12 coated	231 ± 13	220 ± 17	693 ± 21	665 ± 31	332 ± 25	322 ± 11

Table V. Dynamic Impact Test Results.

	Number of ruptured witness papers					
	Spike		S1 blade		P1 blade	
UHMWPE	1.1 J	2.5 J	1.1 J	2.5 J	1.1 J	2.5 J
3 layers of neat	3	4	3	4	4	4
2 layers of Nylon 6,6 coated	1	2	2	3	3	4
2 layers of Nylon 6,12 coated	1	2	2	3	3	4

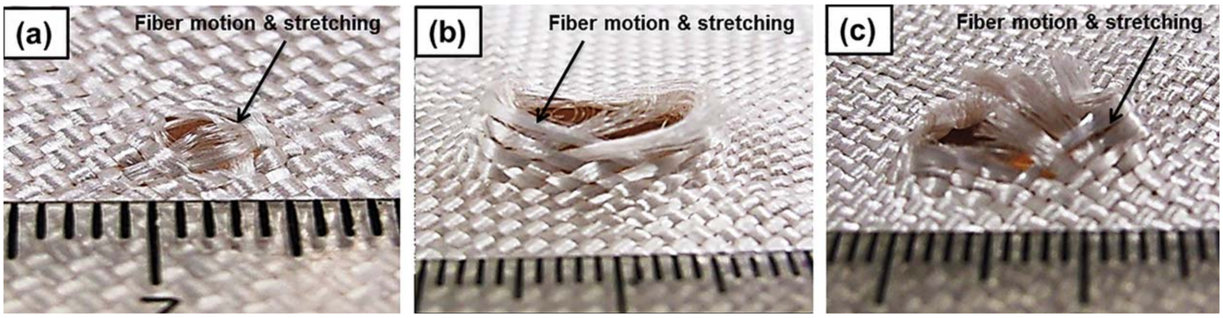

Figure 10. Ruptured areas after quasi-static tests on neat UHMWPE fabric samples using (a) Spike puncture, (b) S1 blade, and (c) P1 blade (millimeter-scale). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

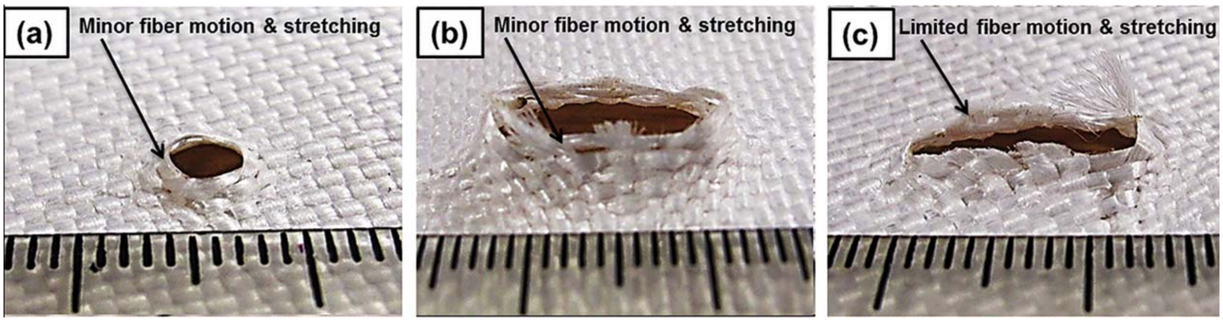

Figure 11. Rupture area after quasi-static tests on Nylon 6,6 coated UHMWPE fabric samples using (a) Spike puncture, (b) S1 blade, and (c) P1 blade (millimeter-scale). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Moreover, although the evidence of fiber breakage was not clearly shown from the images, an acoustic burst sound which was heard at the maximum breaking force may correspond to the local breakage of several close filaments at the same time. In the case of S1 and P1 blades, the filaments were cut along the blade edge after the tip of the penetrator pierced through the

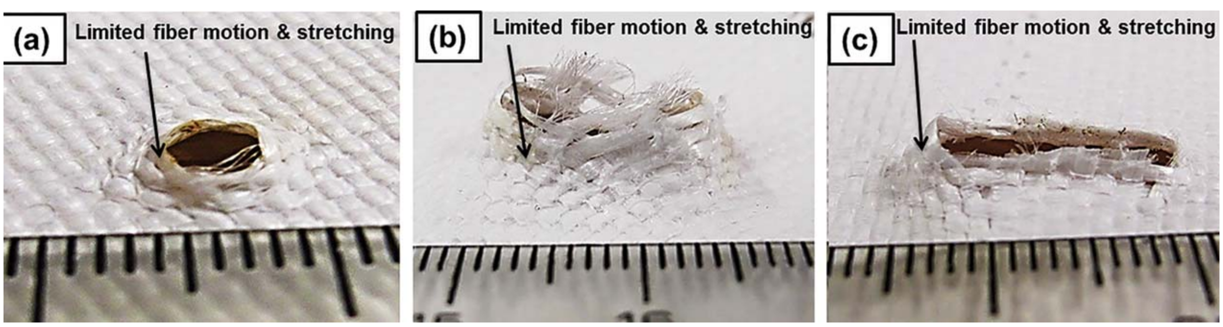

Figure 12. Ruptured areas after quasi-static tests on Nylon 6,12 coated UHMWPE fabric samples using (a) Spike puncture, (b) S1 blade, and (c) P1 blade (millimeter-scale). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

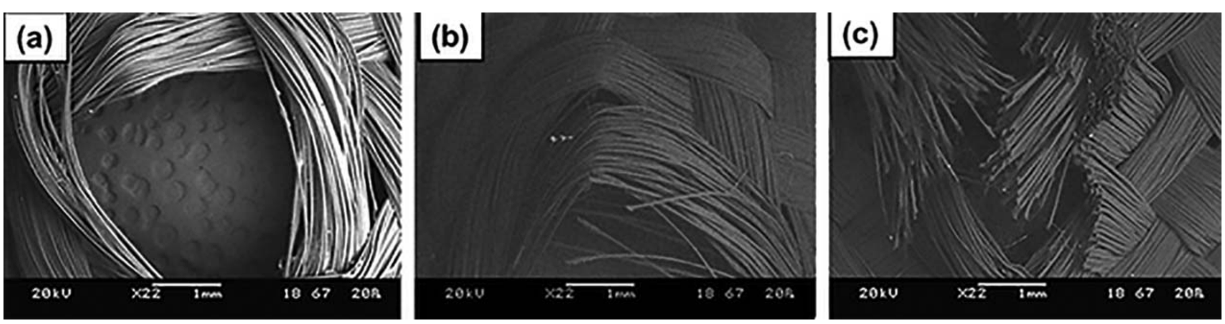

Figure 13. SEM: Ruptured areas after quasi-static tests on neat UHMWPE fabric samples using (a) Spike puncture, (b) S1 blade, and (c) P1 blade.

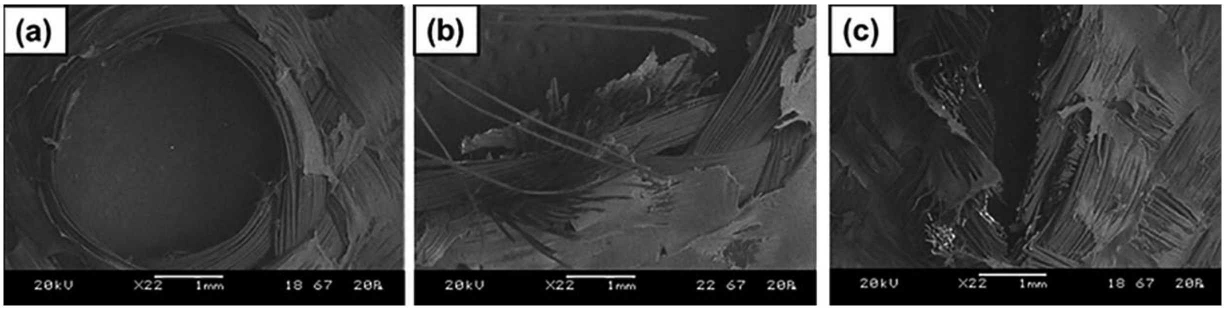

Figure 14. SEM: Rupture area after quasi-static tests on Nylon 6,6 coated UHMWPE fabric samples using (a) Spike puncture, (b) S1 blade, and (c) P1 blade.

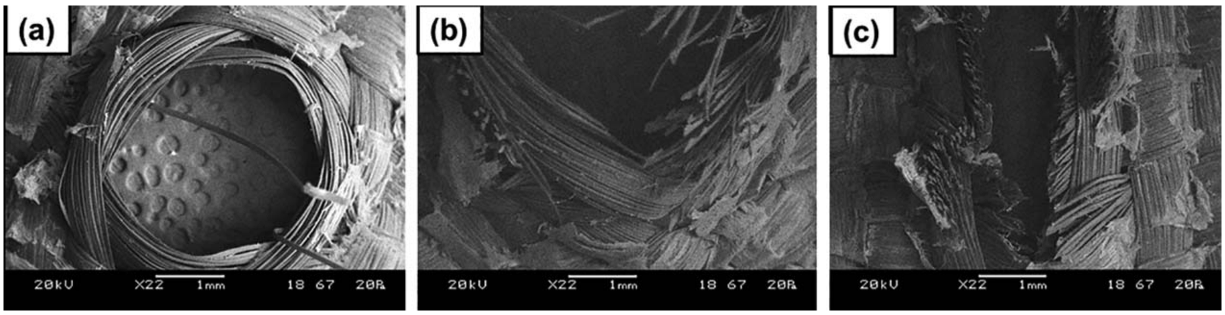

Figure 15. SEM: Ruptured areas after quasi-static tests on Nylon 6,12 coated UHMWPE fabric samples using (a) Spike puncture, (b) S1 blade, (c) P1 blade.

fabric, and the restriction in the mobility of filaments of coated fabric samples became less important for cut resistance (as the cutting mechanism dominated windowing effects). More filament breakages (or cuts) were observed for the nylon-coated UHMWPE fabric samples as they were shown in Figures 10(b,c), 11(b,c), and 12(b,c). In addition, it could be interpreted that blade threats result in more localized cut damage which is opposite to what was observed for puncture threats. These could be the key reason why nylon-coated samples show more improvement over uncoated samples against spike threat but not against S1 and P1 blades. SEM monographs of the ruptured areas [Figures 13–15] confirm what is observed in the photographs; more loose fibers are found in the case of the neat fabric sample, while the fibers remained more close packed when coated with nylon. Moreover, the enhanced resistance of the nylon-coated samples can be attributed to both the increase in resistance to fiber-pull out and coating rupture near the point of impact.

CONCLUSIONS

Mechanical interlocking of Nylon 6,6 and Nylon 6,12 creates a uniform and stable coating on the inherently inert UHMWPE fabric samples as a result of nylon film shrinkage upon drying. Nylon 6,6 or 6,12 coated fabric samples demonstrate more puncture resistance compared to neat UHMWPE fabric sample (2 vs. 3 layers with similar areal densities) with no loss of flexibility and a reduced total thickness requirement affording the same level of stab resistance; this could increase the maneuverability and mobility of the worn security clothing and be a cost effective, thin, and flexible alternative to comparable body armor systems. On the other hand, a single layer of nylon-coated samples also demonstrated superior resistance against both spike and stab threats regardless of the consequent weight increase. We propose that nylon-coated UHMWPE, like Kevlar, is a framework that facilitates extensive hydrogen bonding between amide linkages and other materials, and may be compatible with STF. Further improvements with nylon-coated UHMWPE may be realized by coating individual fibers prior to creating weaved garments. An investigation into the use of nylon coatings on UHMWPE to improve the insulating properties of these materials and its interaction with STF materials are currently under way.

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