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Effect of domestic laundering on the fragment protective performance of fabrics used in personal protection

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Abstract
UK Armed Forces wear items of clothing that incorporate fragment protective fabrics (Tier 1 Pelvic Protection) and other items of clothing are under development (e.g. Improved Under Body Armor Combat Shirt). The long-term robustness of such garments is of interest. In this paper four candidate fabrics (knitted silk, ultra-high molecular weight polyethylene felt, para-aramid felt and a woven para-aramid) were investigated. The effect of laundering on 0.24 g chisel-nosed fragment simulating projectile ballistic protective performance was measured on packs containing the candidate fabrics that were representative of clothing layers. Changes in the physical properties (mass, thickness, dimensional change) of candidate fabrics were measured. The ballistic protective performance of two candidate fabrics was unaffected by laundering; for the other two fabrics improved performance was measured. The masses of the specimen packs was unaffected by laundering; however, the thickness of all fabrics increased, relative to dimensional change.

Keywords
Para-aramid, ultra-high molecular weight polyethylene, silk, ballistic testing

The incorporation of hierarchical fragment protection into combat uniforms (as opposed to body armor) has recently been discussed in the open literature.[1,2] This work suggested the use of one or two layers of fragment protective fabrics incorporated into combat uniforms to provide a degree of protection to the extremities. UK Armed Forces now wear items of clothing that incorporate such levels of fragment protection (e.g. Tier 1 Pelvic Protection, Figure 1) and other items of clothing are being developed (e.g. Improved Under Body Armor Combat Shirt (IUBACS), Figure 2). Other nations now use similar items of clothing. Ballistic protective clothing in use with the British Armed Forces has used knitted silk to provide the base level of protection.[2] Other materials of interest for this application include ultra-high molecular weight polyethylene (UHMWPE) felt, para-aramid felt (PAF) and woven para-aramids (WPAs).

The long-term robustness of such garments is critical. Inter-layer wear with reference to fabrics typically used in police and military body armors has been discussed.[3,4] The effect of moisture on typical ballistic protective fabrics has been previously investigated.[5,6] Some of this work identified that removal of lubricants from the weaving process may result in improved performance, as the friction between yarns will increase.[7–9] Although military body armor protective packs are rarely laundered, combat clothing (including Tier 1 and UBACS) is routinely laundered. Laundering is one of the most aggressive degradative agents a fabric is exposed to during use, resulting in changes in physical and mechanical properties.[10–12] Therefore, whether laundering affects fragment protective clothing is of interest.

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The aim of this work was to determine the effect of multiple domestic washing and drying cycles on the fragment protective properties of packs representative of fragment protective clothing. Dimensional stability, mass and thickness of specimens were also considered with reference to possible shrinkage of clothing.

Figure 1. Tier 1 pelvic protection.

Materials and methods

The effect of laundering on four fabrics was assessed. Specimens (400 mm × 400 mm) were manufactured using two layers of fabric encased in a disruptive pattern polyester–cotton fabric (70% polyester 30% cotton; twill 3/1; 12 × 12 yarns/10 mm, 175 g/m^2). Specimens were quilted using stitch type 301 every 100 mm (e.g. Figure 3).[13] Each of the fragment protective fabrics was provided in the loom state.

The four fabrics under investigation were as follows:

- single jersey knit silk (SJKS), 130 g/m^2;
- hydro-entangled UHMWPE felt (HEUF), 200 g/m^2;
- para-aramid felt (PAF), 200 g/m^2;
- woven para-aramid (WPA), 156 g/m^2.

Four sets of specimens were prepared for each fabric; set one was not laundered. The remaining specimens were washed with laundry detergent (Detergent Laundry NATO Stock Number: 7930992251626) for either 9, 18 or 27 cycles using a Bosch Logixx 8 VarioPerfect WAS32460GB washing machine set at a mixed load program and 40°C, 45 min wash with spin speed of 800 rpm. Specimens were then dried after each washing cycle using a Bosch Exxcel Condenser WTE86308GB tumble drier (cupboard dry cycle,

Figure 2. Improved Under Body Armor Combat Shirt (IUBACS) concept demonstrator.

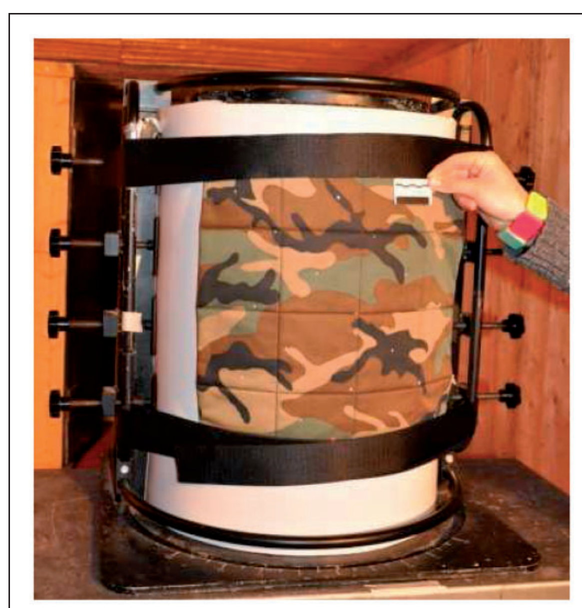

Figure 3. Typical specimen mounted for ballistic testing.

approximately 90 min). These conditions were chosen to represent typical in-use laundering by service personnel and are recommended on the garment's care label. Personnel are issued with multiple sets of items such as Tier 1 pelvic protection for an operational tour, and 27 laundering cycles approximates the number of times items would be laundered on operations before replacement.

After laundering, specimens were conditioned according to ISO 139: 2005 for a minimum of 24 hours according to ISO 139: 2005 (20°C ± 2°C; 65% relative humidity (RH) ± 4% RH).[14] The effect of laundering on 0.24 g (four-grain) chisel-nosed fragment simulating projectile (CN FSP)[15] V_{50} data was determined. (The V_{50} is the velocity at which there is a statistical probability of 50% of a given projectiles completely perforating the target.) A number 3 Enfield proof mount fitted with an L85 (SA80) barrel was used to fire FSPs, which were placed in a polymeric sabot and fired by adjusting the mass of Vihtavuori N330 propellant used in hand-loaded 5.56 mm × 45 mm L15A2 cartridge cases (manufactured by Radway Green between 1998 and 2001). All specimens were mounted on the UK Ministry of Defence (MoD) behind armor blunt trauma (BABT) rig described by Cannon.[16] Due to the low energy levels involved in these impacts, no BABT assessment was conducted in this work. Specimens were placed approximately 5 m from the end of the muzzle. A Doppler radar system was used to measure the velocity of the projectiles (see Figure 4 for a diagram of the range setup). FSPs were fired at each specimen in such a manner that no impact occurred within 50 mm of the specimen edge; 50 mm from a previous impact; and avoiding previously impacted warp, wale or '*x*' and weft, course and '*y*' yarns or orientations. Whether or not the FSP perforated the specimen was noted. During the tests the temperature and RH were recorded (mean temperature: 20.0°C, SD 1.1°C; mean RH: 40.7%, SD 5.2%), along with the charge mass and the velocity of the projectile.

Estimated 0.24 g FSP V_{50} data were calculated using the DSTL Critical Perforation Analysis (CPA) tool based on the R statistical software package.[17] The CPA tool calculates the V_{50} based on the Probit statistical method.[18–20] The tool used the bias reduction estimation procedure for the standard generalized linear model introduced by Firth.[18] This is a method that adjusted the estimation process to ensure that the standard errors produced are finite and lead to meaningful confidence intervals and inference using regression models with binary outcome data. Using the CPA tool, the standard error and the 95th percentile confidence limits of each V_{50} were calculated. Calculating the confidence limits provides an indication of the variability in the ballistic performance of each of the specimens. Between 35 and 39 data points were used in each calculation of the V_{50} and the confidence limits.

A Probit regression model was fitted to the ballistic performance data.[19] This model was used to compare the number of laundering cycles to determine if there was any significant difference in the V_{50} for each condition. The differences were assessed using a Wald test[21] on the model parameters. The non-laundered data was the baseline group.

Damage to the fabric specimens was investigated using a JEOL 6700F field emission scanning electron microscope (FESEM; lower electron image (LEI) detector, 3 kV, 8–17 mm working distance); specimens were mounted on aluminum stubs with double-sided carbon tape and sputter coated with gold palladium using an Emitech K575X Peltier-cooled high-resolution sputter coater. Surface debris was identified using a JEOL JED 2300F energy dispersive spectrometry (EDS) detector (25 kV) using point analysis; areas were identified using a back scatter detector. The typical images were taken from areas of the samples chosen to be more than 100 mm from any edge and not in an area disrupted by quilting or ballistic impact.

Specimen dimensional change was measured using BS EN 5077:2008[22] and change in thickness was

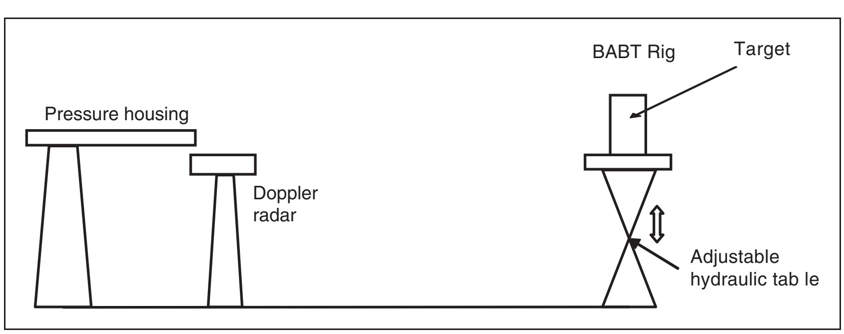

Figure 4. Range setup used in the ballistic trials. BABT: behind armor blunt trauma.

measured using a Mitutoyu dial-thickness gauge in accordance with ISO 5084:1996.[23]

Results and discussion

The effect of laundering on ballistic performance is summarized in Table 1. Data for laundered specimens are normalized against results for non-laundered specimens. (Actual performance data cannot be quoted as these relate to the protection afforded by in-service equipment and is classified information.)

There was no difference in the ballistic protective performance of the SJKS and HEUF specimens between non-laundered and 9-cycle laundered, non-laundered and 18-cycle laundered, or non-laundered and 27-cycle laundered (p-value > 0.05).

There was strong evidence of a difference in the performance of the PAF and WPA specimens between 0 and 9 laundering cycles (p-value < 0.01). There was no evidence of a difference between 9 laundering cycles and 18 laundering cycles, or 18 laundering cycles and 27 laundering cycles for these two fabrics (p-value > 0.05).

All fabrics showed a statistically significant change in physical properties due to laundering (p-value < 0.01) (Tables 2–5).

The SJKS shrank in both the wale and course directions. The shrinkage in the course direction was greater than in the wale direction. The HEUF and PAF shrank reasonably uniformly in both the 'x' and 'y' directions. The WPA shrank more in the warp direction than in the weft direction. As expected, the two felted fabrics shrank more after laundering than the SJKS or the WPA.[24] The reductions in the two dimensions were matched by a corresponding increase in the thickness of the samples. The increase in thickness did not correspond to the change in ballistic protective performance. However, the increased thickness of the samples would be expected to increase the thermal resistance of

Table 1. Summary data of relative ballistic performance compared to baseline

	SJKS		HEUF		PAF		WPA	
Number of cycles	V_{50} (%)	SE (%)	V_{50} (%)	SE (%)	V_{50} (%)	SE (%)	V_{50} (%)	SE (%)
0	100.0	2.8	100.0	2.5	100.0	2.8	100.0	2.7
9	103.9	1.4	102.6	4.8	116.5	2.3	114.3	2.5
18	102.4	3.1	99.7	2.7	112.2	1.9	119.9	3.5
27	102.0	2.7	100.6	2.4	115.8	2.7	113.0	4.1

SJKS: single jersey knit silk; HEUF: ; PAF: para-aramid felt; WPA: woven para-aramid.

Table 2. Changes in physical properties for single jersey knit silk (SJKS)

	Mean dimension wale (%)	Standard error (%)	Mean dimension course (%)	Standard error (%)	Mean thickness (%)	Standard error (%)
Baseline	100.0	0.0	100.0	0.5	100.0	1.0
9 Cycles	97.5	0.0	95.5	1.0	114.0	0.0
18 Cycles	97.5	0.0	95.0	1.0	123.0	4.5
27 Cycles	98.5	1.0	98.0	0.5	116.0	0.5

Table 3. Changes in physical properties for HEUF

	Mean dimension 'x' (%)	Standard error (%)	Mean dimension 'y' (%)	Standard error (%)	Mean thickness (%)	Standard error (%)
Baseline	100.0	0.0	100.0	0.0	100.0	3.0
9 Cycles	94.5	0.5	96.5	0.0	140.5	5.5
18 Cycles	92.5	0.5	93.5	0.5	165.0	3.5
27 Cycles	91.0	0.5	91.0	0.5	164.5	8.0

Table 4. Changes in physical properties for para-aramid felt (PAF)

	Mean dimension 'x' (%)	Standard error (%)	Mean dimension 'y' (%)	Standard error (%)	Mean thickness (%)	Standard error (%)
Baseline	100.0	0.5	100.0	0.0	100.0	1.5
9 Cycles	97.0	0.5	97.5	0.5	119.0	4.5
18 Cycles	94.0	0.5	96.5	0.5	135.0	8.5
27 Cycles	94.0	0.5	95.5	0.5	128.0	1.0

Table 5. Changes in physical properties for woven para-aramid (WPA)

	Mean dimension warp (%)	Standard error (%)	Mean dimension weft (%)	Standard error (%)	Mean thickness (%)	Standard error (%)
Baseline	100.0	0.0	100.0	0.0	100.0	2.5
9 Cycles	97.5	0.0	99.0	0.0	105.5	1.5
18 Cycles	96.5	0.0	98.5	0.0	107.0	1.0
27 Cycles	96.5	0.0	98.0	0.0	110.0	0.5

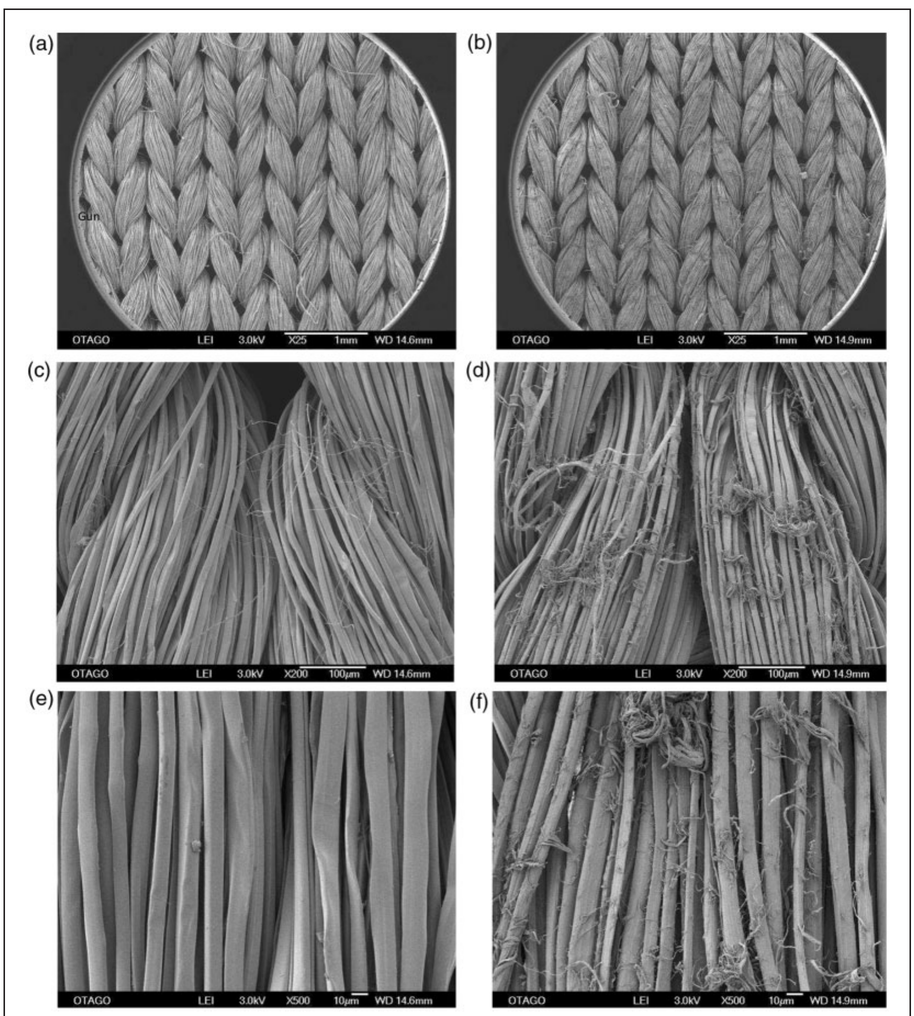

Figure 5. Field emission scanning electron microscope (FESEM) images of single jersey knit silk (SJKS) before and after laundering: (a) 0 cycles; (b) 27 cycles; (c) 0 cycles; (d) 27 cycles; (e) 0 cycles; and (f) 27 cycles.

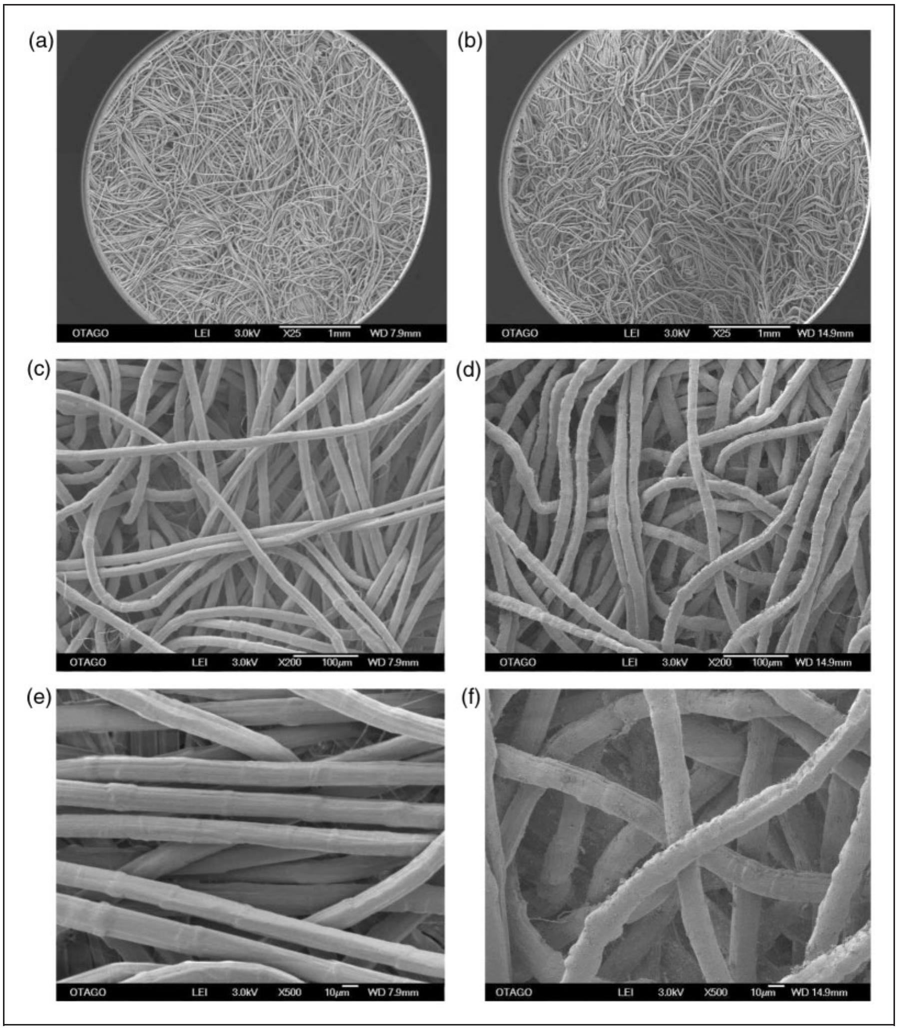

Figure 6. Field emission scanning electron microscope (FESEM) images of HEUF before and after laundering: (a) 0 cycles; (b) 27 cycles; (c) 0 cycles; (d) 27 cycles; (e) 0 cycles; and (f) 27 cycles.

the garments[25] and resulted in changes in its appearance.[11] In comparison, there was no significant change in the mass of the specimens, indicating no loss of fiber due to laundering. Ballistic protective clothing that incorporates felts would be more severely affected by laundering than the knitted or woven fabrics examined in this study.[24]

Typical examples of the images obtained using the FESEM are given in Figures 5–8. The silk and para-aramid fibers were degraded through laundering by surface peeling of the fibers. This type of damage has been previously reported for both silk and para-aramid fibers and may be indicative of a loss in tenacity of yarns and fabrics.[4,12] The peeling of the surface of the fibers might increase the friction between yarns. There is evidence that increasing the friction between yarns can affect the ballistic protective performance of fabrics;[26] this might account for the increase in ballistic protective performance of the two para-aramid fabrics after laundering. Another possible contribution to the change in fabric ballistic performance may be due to the lubricants used in the manufacturing process having been removed during laundering. These lubricants are added to the yarns in the weaving/knitting process to improve the quality of the fabric and reduce damage to the fibers. It is known that fabric that has been 'scoured' has shown improved ballistic performance to identical fabric in the loom state.[8,9,27] The polyethylene fibers exhibited a different degradative mechanism via localized swelling and longitudinal splitting. Such degradation does not appear to have been previously reported. This damage to the fibers does not appear to

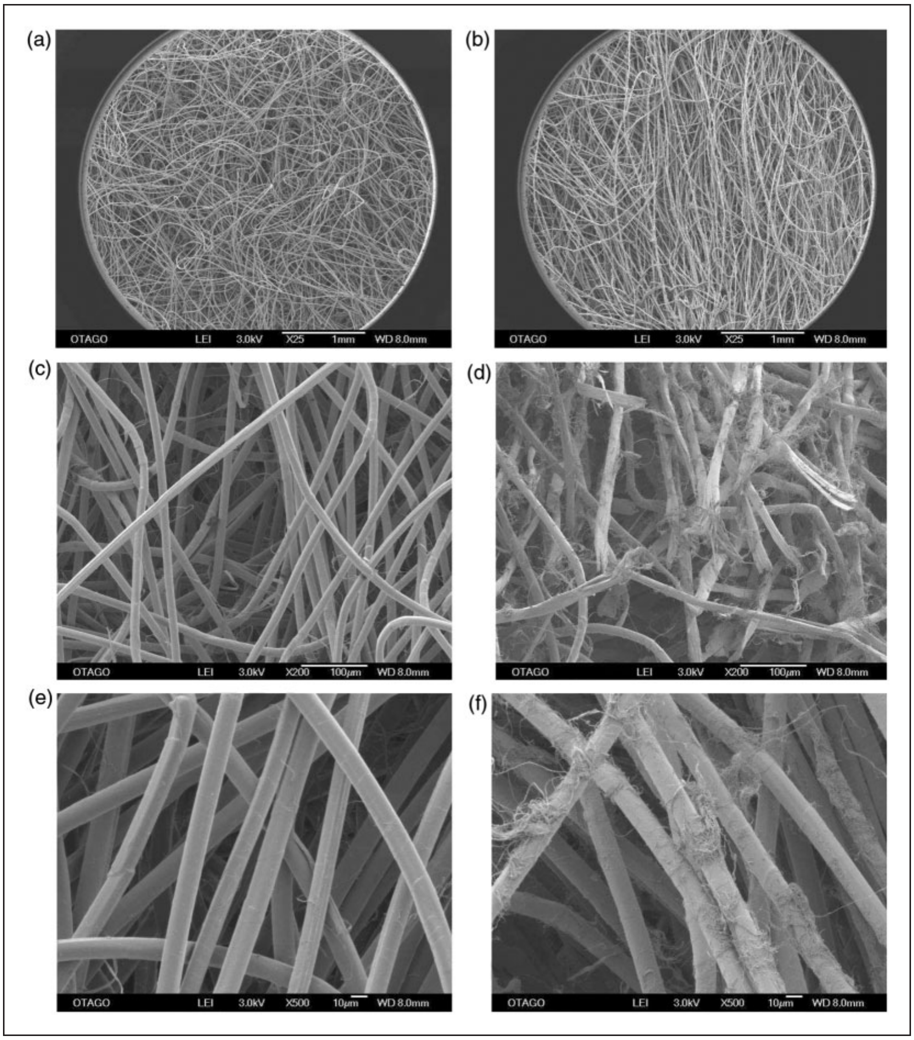

Figure 7. Field emission scanning electron microscope (FESEM) images of para-aramid felt (PAF) before and after laundering: (a) 0 cycles; (b) 27 cycles; (c) 0 cycles; (d) 27 cycles; (e) 0 cycles; and (f) 27 cycles.

have resulted in any change in ballistic protective performance.

Foreign surface debris observed in specimens after laundering was identified as laundry detergent residue through EDS analysis; elements identified were 55% Ca, 26% S, 10% P and 8% Si (excluding common elements and those present in the coating used in the FESEM).

Conclusions

The data collected suggested that the ballistic protective performance of SJKS and HEUF measured using 0.24 g FSPs was not affected by up to 27 laundering cycles. The PAF and the WPA showed improved performance against the 0.24 g FSP after 9 laundering cycles. It is not known at this time whether laundering at higher temperatures will affect these results. Whether this increase in performance is due to the removal of the lubricants used in knitting/weaving or the surface peeling of the fibers and hence an increase in friction between fibers/yarns is uncertain.[26,27]

Changes in the dimensions for the PAF and the HEUF resulted in a significant decrease in the surface area of the fabric panels. The SJKS and WPA showed only a slight decrease in fabric surface area. The respective increases in thickness followed the same trend as changes in dimensions. This information is important not only because the dimensional change on laundering might contribute towards the changes in ballistic performance identified, but also due to changes in appearance and thermal resistance in combat clothing.

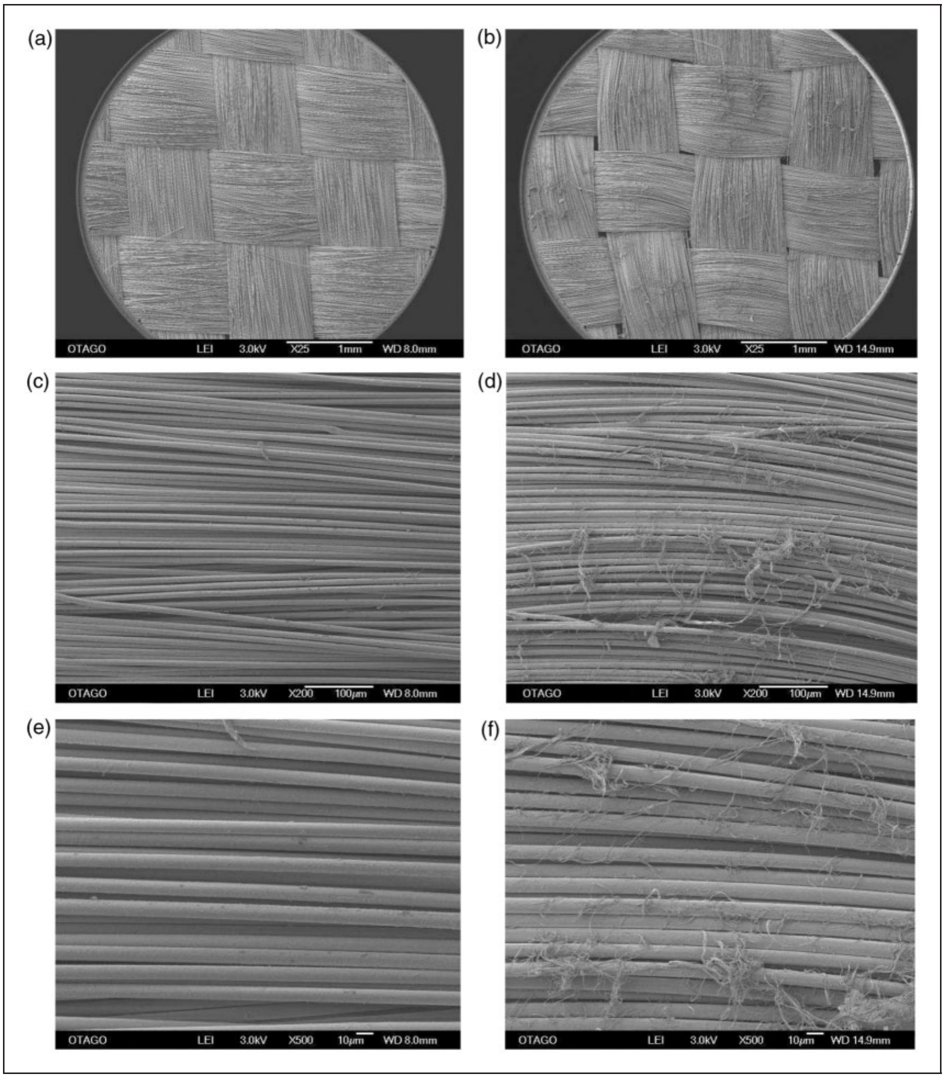

Figure 8. Field emission scanning electron microscope (FESEM) images of woven para-aramid (WPA) before and after laundering: (a) 0 cycles; (b) 27 cycles; (c) 0 cycles; (d) 27 cycles; (e) 0 cycles; and (f) 27 cycles.

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