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Textile sensors for stab and cut detection

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Abstract. Manufacturers are aiming for more flexible and lightweight protective clothing to increase wearing comfort. A cardigan with a knitted stab-resistant inlay and an alarm system is presented. The stab-resistant inlay is based on a multilayer ultra-high molecular weight poly ethylene (UHMW-PE) fabric. Stab resistance was evaluated according to the standard of the Association of Test Laboratories for Bullet, Stab or Pike Resistant Materials and Construction Standard (VPAM 2011). Furthermore sensors for the detection of cuts and pressure were integrated. Both sensors can trigger alarms if the wearer is attacked. Normal pressure occurring through leaning on a wall or sitting is filtered out and does not trigger an alarm.

1. Introduction

Between 1997 and 2005 stabbing attacks involving a knife or other sharp instruments resulting in the hospitalization of victims have increased about 30 % in England. [1] Furthermore, reports of spectacular lethal attacks on public service employees lead to a more decreased security feeling in the population.

Generally, flexible materials like knitted textiles do not offer a good resistivity to cuts. Only few yarns have a high Young's modulus, which makes them suitable for protective gear. The best-known yarn is aramid, but also poly(p-phenylene-2,6-benzobisoxazole (PBO) and ultra-high molecular weight poly ethylene (UHMW-PE) were investigated for this application. [2, 3] Also the influence of knitting techniques and mesh sizes were evaluated. [3]

Consequently, a merino wool jacket with a stab resistant inlay of UHMW-PE was developed. [4]

The destruction of the inlay-fabric can be detected with sensors. [5] Events indicating a change in the electric circuit, e.g. a resistivity change due to a rupture in the circuit or a change in the time-dependent decharging-time of a capacitor, trigger an alarm. Capacitive sensors are known in smart and wearable textiles to detect motion and pressure changes on the human body [6].

The aim of this work was bringing together these features in one jacket: offering an unremarkable stab resistant jacket with an alarm system (stab sensor) and in case of assaults, where the protective fabric is destroyed; a second sensor detects the violence and could give out an emergency call to a coordination center.

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2. Built-up of sensor inlay

The jacket was constructed to be seamlessly knitted with a composite yarn of wool and UHMW-PE. The stab protection inlay and the sensor textiles were tailored subsequently in three parts: one back and two front parts. The built-up of the protection layers and the location of the sensors is shown in figure 1. The stab protection layers are also made of UHMW-PE.

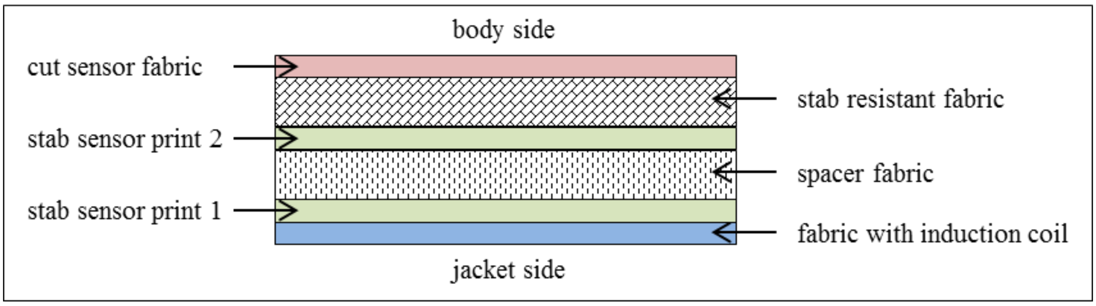

Figure 1: Schematic built-up of jacket inlay

In the jacket inlay four functionalities are put together: one sensor for the detection of cuts, meaning destroyed fabrics, one stab resistant fabric layer, one sensor for the detection of stabs, which to not destroy the fabric and on the outside an induction coil for the charging of the evaluating device.

2.1. Sensor for cut detection

Several conductive yarns were evaluated for the cut sensor fabrication. Important parameters were knitting feasibility, conductivity before and after the knitting process and stab resistance. Therefore different metalized yarns were investigated: steel staple fibres, silver coated yarns (Shieldex®), Bekinox, Amberstrand (Ag and Ni).

In order to detect a cut in the jacket, a matrix-like structure of conductive yarn (Shieldex 235/34 2-ply) was embedded in the first layer of stab-resistant cloth (figure 2).

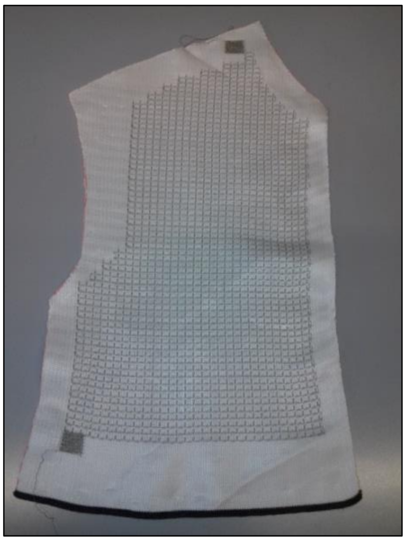

Figure 2: Knitted cut sensor (left front side of cardigan)

The white panels are 0.7 cm^2 so that a penetrating blade would definitely cut through the conductive yarn early on. That would lead to a detectable change in resistance, which would trigger an alarm to go off. The whole system is knitted out of one thread and therefore easy connect at the small panels on the upper shoulder and near the waist. The panels can be positioned freely at the beginning

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and the end of the matrix, but prove to be the least hindering at these points of the body. They were connected to the evaluating unit with push buttons, on which insulated copper wires were soldered.

2.2. Sensor for pressure and stab detection
This sensor was built up through a capacitor matrix. Therefore stripes of conducting ink were screen printed on a polyester fabric with a screen of 60 mesh. The stripes were 50 mm wide and had a distance of 5 mm. The number of stripes depended on the dimensions of the tailored fabric. The ink used was Tubicoat ELH from CHT R. Beitlich, Tübingen, Germany. All fabrics were printed before tailoring. On one fabric the stripes were printed in longitudinal direction, and the second in cross direction. Putting these fabrics together the capacitor matrix is built-up. In order to enhance the capacitance, a spacer fabric was installed between the printed fabrics. Each stripe was connected to the electronic evaluation unit using wires soldered on metallic push buttons (see figure 3).

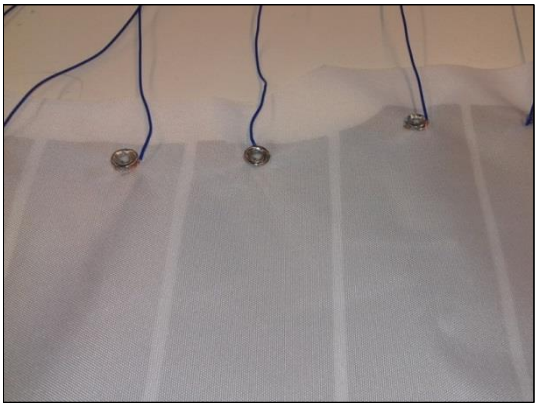

Figure 3: Tailored back part for pressure and stab detection

2.3. Evaluating unit and power supply
The jacket was furnished with a pocket in the inside to hold a miniaturized evaluating unit. Even small changes of capacity and resistivity were detected and an alarm triggered. The alarm can be sent using a smartphone to coordination center.

Rechargeable batteries ensure the power supply of the evaluating unit. They can be constantly charged via an induction coil on the outside of the inlay. A copper wire was embroidered circularly on the back part of the inlay as coil. The wire was coated with an insulating lacquer, which melted upon soldering. The fabric was a linen cloth. The counterpart is adjusted on a seat and connected to a power grid and is also an embroidered copper wire on cotton fabric.

2.4. Characterizations of sensors
The abrasion fastness of the sensors was investigated using the Martindale abrasion test standard procedure. Washing fastness of printed sensors and knitted conductive yarn was examined in 3 cycles of 30 °C household wash with a special washing program for wool.

The conductivity of the yarn for the cut sensor was determined using a Milli-TO 3 Ohm-Meter from Fischer Elektronik and the sheet resistance of the printed conductive stripes was checked using a MR-1 Ohm-Meter from Schuetz-Messtechnik. Scanning electron microscope figures were taken with a TM 3000 from Hitachi.

The stab resistant fabric was examined according to the VPAM examination instruction “Stich- und Schlagschutz” (stab and hit protection). According to this specification, a defined blade in shape and sharpness falls, driven by a weight of 2.5 kg and led by rails, through the fabric under examination into a box filled with plasticine from a height of 30 cm [7].

3. Discussion

The different conductive yarns were evaluated regarding their physical and mechanical properties. Main parameters were knitting feasibility and the behavior of the conductivity under mechanical and physical stress. The resistance of the used yarns before mechanical strain is given in Table 1.

All yarns except the Shieldex yarns show high abrasion on the knitting machine. Two effects are observed: the resistance of the processed yarns increased and the abraded particles are found on the fabric, mainly consisting of polyester yarn. In case of the steel staple-fiber, also yarn breaks were observed, which led to a complete loss of electrical conductivity after knitting.

Table 1: Resistance of investigated yarns before knitting

Material	resistance [Ω/m]
Shieldex 235/34 2-ply HC+B	115
Shieldex 117/17 2-ply HC+B	190
Amberstrand 166-Ag	3,5
Amberstrand 166-Ni	3,25
Bekinox VN 12	32
steel staple-fiber	3700

Also the washing fastness of these yarns was evaluated. Also in this test the Shieldex yarns showed the best performance. Consequently they were chosen in the production of the cut sensor.

The washing fastness of the cut sensor is shown in figure 4. With an increasing number of washing cycles the resistivity of the conductive yarn raises. In this test a knitted fabric for the front part of the jacket was examined. The conductive yarn was embedded in a matrix-like structure (see figure 2)

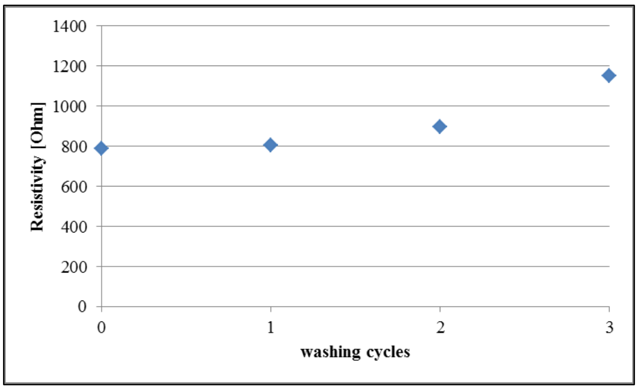

Figure 4: Influence of household wash at 30 °C to the resistivity of the cut sensor

Already after three washing cycles at 30 °C the resistivity of the sensor raised from 800 Ω to nearly 1200 Ω (figure 4). The loss of conductivity can be explained by abrasion or by washing out of the conductive coating on the yarn. The precise reason was not further examined in this work.

The sensor for stab detection reacts on pressure changes. The fabric need not be destroyed for triggering an alarm. Only one conductive ink was evaluated.

The resistance of the conductive bars of the capacitive sensor changes slightly changes during the abrasion test. Initially a resistance of 100 Ω was measured. After 10,000 Martindale cycles, the sheet resistance of the meander dropped slightly to 90 Ω and did not change until the abrasion test was stopped after 50,000 Martindale cycles. Before the abrasion test, some conductive particles are visible in the SEM micrograph (figure 5, left). The surface of the conductive meander after 10,000 Martindale cycles looks smoother than before the abrasion test (figure 5, right). The microstructure of the printed conductive meander did not change further until the abrasion test was stopped.

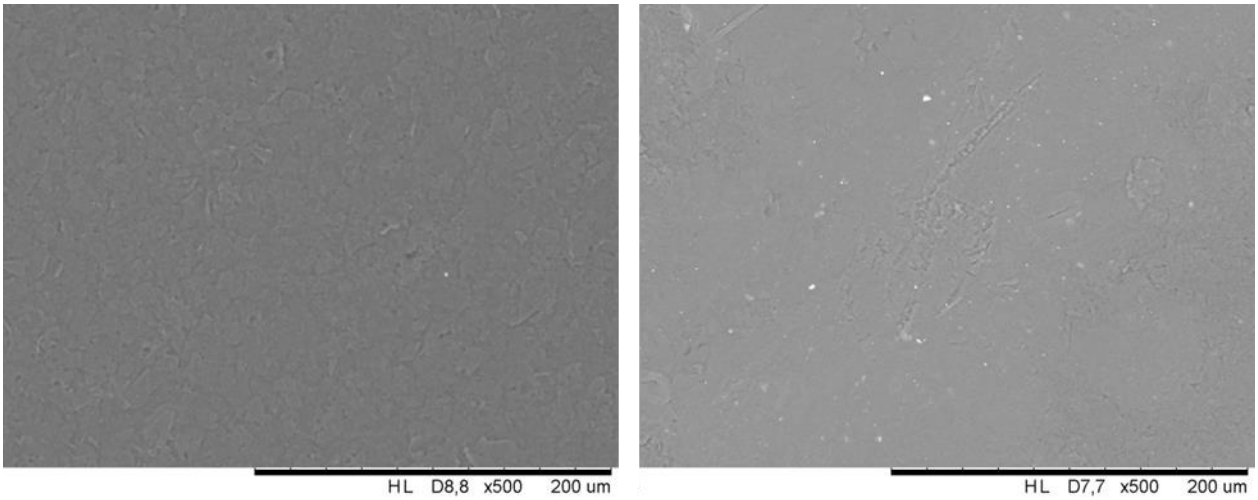

Figure 5: SEM-micrographs of stab sensor before Martindale test (left) and after 10,000 Martindale cycles (right)

The capacity of on matrix elements is 200 pF. A punctual force on the joint stab sensor fabrics leads to a small change of the capacity, which can be detected. The resulting evaluation depends on the strength of the influencing force. Large capacity changes, which occur, when a person is leaning against a wall or seat, are filtered out. Also very small capacity changes due to the natural movements of a person are not detected.

Because the sensor is not resistant to washings, it must be calibrated after each washing cycle, which is not practicable. The inlay was attached to the jacket by Velcro®-fasteners, which can be opened for washing and allow the inlay to be removed prior to cleaning.

The tailored and joint inlay is shown in figure 6.

Figure 6: Tailored jacket inlay with induction coil and Velcro® strips for fastening

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4. Conclusions

A protection jacket with sensors for stab and cut detection was presented. The sensor for cut events was a meander knitted with conductive yarn and the sensor for stab events was a printed capacitor matrix. A small detection unit evaluates cuts and small pressure changes triggering an alarm. The alarm can be a sound at the scene or it can be transmitted to a coordination center via smartphone, or both.

The printed pressure sensor meander shows an extremely high abrasion fastness. Even after 50,000 Martindale cycles the conductivity was not negatively influenced.

Another important property is the washing fastness of the inlay. The stab resistant fabric and the induction coil show excellent results. The conductivity of the latter is only slightly influenced and washing is known to improve the stabbing resistivity of the UHMW-PE. [4] But the two sensors are sensitive to washing. Therefore the whole inlay can be removed from the jacket prior to washing. This extends the life-time of the sensors and avoids a necessary calibration after each washing.

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References

[1] Maxwell R, Trotter C, Verne J, Brown P, Gunnell D 2007, J. Pub. Health, **29**, 186–90

[2] Li C S, Huang X C, Li Y, Yang N, Shen Z, Fan X H 2014 *Polymers for Advanced Technologies* **25** 1014–19

[3] Weber M O, Aumann, S, Vidzem B, Obermann M, Brücken A, Ehrmann A, Bache T, 2014 *47th IFKT Congress*, Izmir, Turkey, 25. –26. September 2014

[4] Weber M O, Aumann, S, Brücken A, Ehrmann A, Bache T, Beck S C, 2014 *Proc. of 8th Aachen-Dresden Int. Textile Conf.*, Dresden, Germany, 27. –28. November 2014

[5] Breckenfelder C, Lempa E, Graßmann C, Topp K, 2016 German Patent DE102015106226A1,

[6] Meyer J, Lukowicz P, Tröster, G 2006, 10th IEEE Int. Symp. on Wearable Computers, Montreux, Switzerland, 11.–14. October 2006

[7] NN, Vereinigung der Prüfstellen für angriffshemmende Materialien und Konstruktionen (VPAM) 2011 Prüfrichtlinie Stich- und Schlagschutz, VPAM-KDIW 2004