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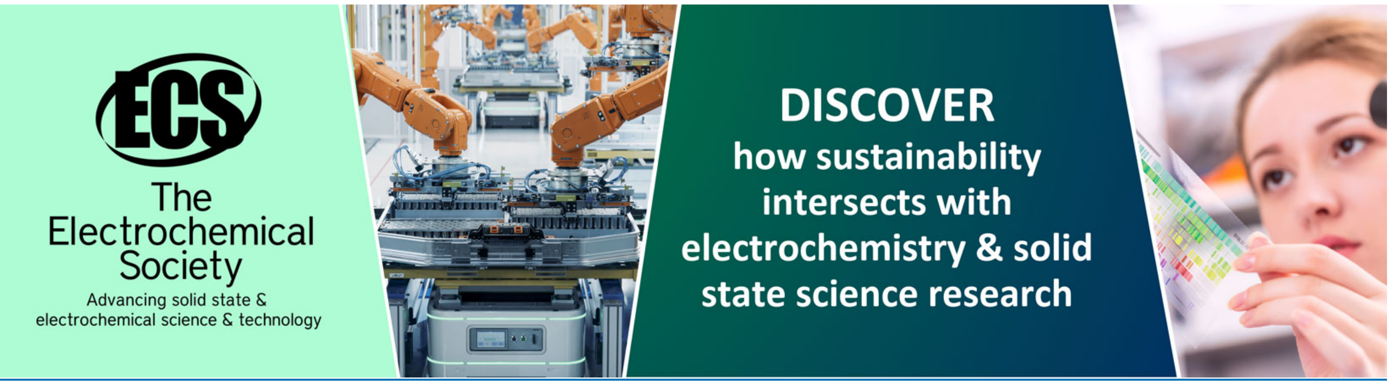

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Comparison Of Flat-Knitted Structures Made Of Poly(P-Phenylene-2,6-Benzobisoxazole) And Para-Aramid Referring To Their Stab Resistance

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Abstract. In the field of protective gear, developers always aim for lighter and more flexible material in order to increase the wearing comfort. Suppliers now work on knitted garments in the sports-sector as well as in workwear and protective gear for policemen or security-agents. In a recent project different knitted structures made of a poly(p-phenylene-2,6-benzobisoxazole) (PBO)-multifilament were compared to their counterparts made of para-aramid. In focus of the comparison stood the stab-resistance linked to either the mass per unit area or the stitch density. The tested fabrics were produced on hand flat knitting machines as well as on electronical flat knitting machines of the type Stoll CMS 330TC4, in order to analyse fabrics with different tightness factor and machine gauges. The stab resistance of the different knitted fabrics was examined according to the standard of the Association of Test Laboratories for Bullet, Stab or Pike Resistant Materials and Construction Standards. The presentation includes the depiction of the results of the test series and their interpretation. Furthermore it will give an outlook on most suitable combinations of materials and structures to be used in protective gear.

1. Introduction

Personal protective equipment is not only necessary for professionals, which are exposed to an increased risk of work-related potential, such as police officers, security guards, bodyguards, etc., but even in occupations where the risk potential does not appear obvious. In Germany, there are augmented reports of violence against people working in public jobs. Especially thrust weapons are used in such attacks. A practical protection of this vulnerable group of people appears more and more necessary [1,2]. Professionals like police officers are using special protective clothing (e.g. ballistic protection made of woven para-aramid or ultra-high-molecular-weight Polyethylene with integrated knife protection) [3]. In this application the protective effect is in focus while the wearing properties are getting secondary attention. Available on the market for civilians to protect themselves from knife attacks are mainly protective vests with integrated metal plates. Their highest disadvantage is the low wearing comfort due to their stiffness and high weight. In a recent project the Niederrhein University of Applied Science in cooperation with the knitting factory Bache Innovative developed a knitted jacket with integrated stab protection as a possible alternative [4,5]. In focus of this investigation which was inspired by a chain mail were not the protection requirements that apply to security officers, it was rather trying to find a compromise between sufficient stab protection and a comfortable

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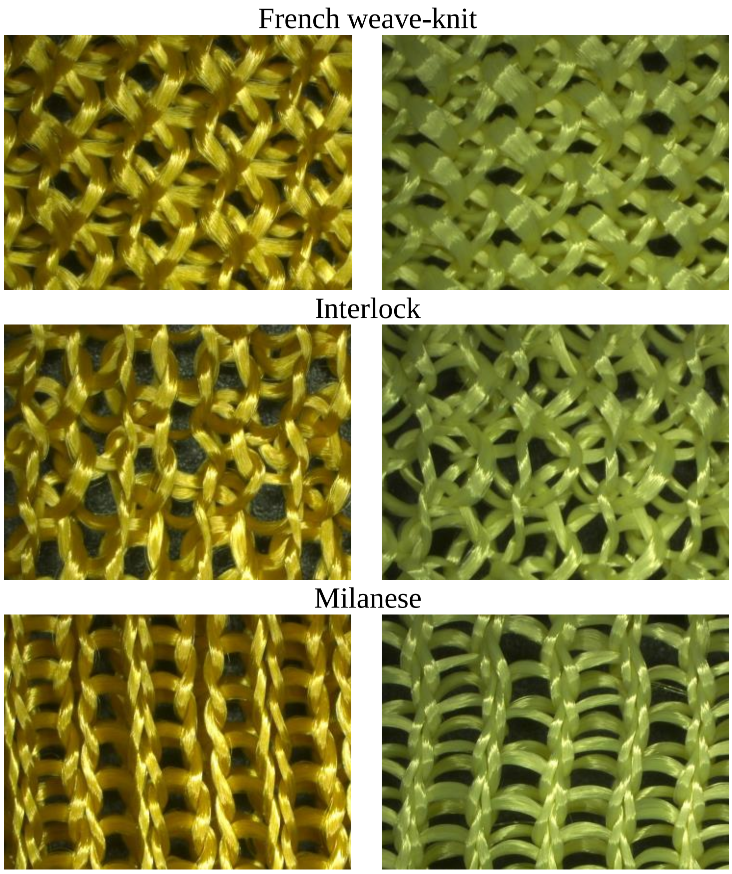
fit. To reach this goal the advantages of knitted structures like the high flexibility and the breathability were combined with the properties of high-tensile polyethylene such as the low density and the high strength. To improve the stab resistance other materials have to be tested. A group of researchers also studied the stab resistance of multi-layered knitted fabrics made from para-aramid (poly-pentamethylen-perephthalat) and PBO (poly(p-phenylene-2,6-benzobisoxazole). They came to the conclusion that PBO-knitted fabrics are more suitable for textile stabbing-protection than PPT [6]. In the work described here, different knitted structures made of a PBO-multifilament were compared to their counterparts made of para-aramid.

2. Experimental

2.1. Knitting

Based on former experiments, four different structures were produced on an electronic flat-knitting machine of the type STOLL CMS 302 TC with gauge E8. Using Zylon AS (PBO) with a thickness of 555 dtex, the structures Milanese, French weave-knit, interlock and spacer-fabric were knitted. The same structures were manufactured using Twaron Type 2040 (para-aramid) with a thickness of 550 dtex (Figure 1). While knitting, the cut-resistant properties of the yarns led to difficulties, since the yarn would not break, when stretched too much, it would rather break the needles and bend the needle-bed. Due to this fact, the size of the loops got slightly increased. The speed of the fabric take-down was also decreased, since the used filaments are very sleek, so that the out-coming fabrics slipped through the cylinders. To minimize the risk of faulty stitches in the fabric, the knitting-machine was set on slow speed.



Spacer fabric

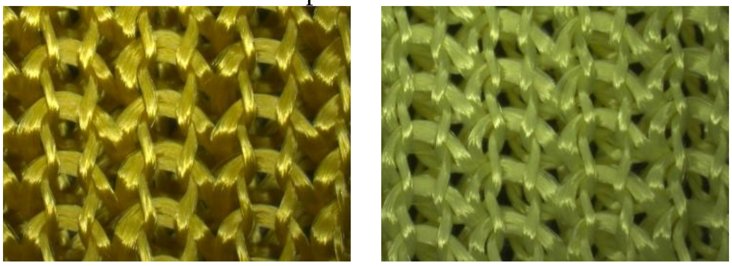


Figure 1. Microscopic pictures, 20 x zoom, PBO (left panels) and aramid (right panels).

While testing, it was observed that the PBO-fabrics developed peculiar craters that differed from the ones of aramid and UHMWPE (Ultra-high-molecular-weight polyethylene) fabrics (figure 2). They were steeper and deeper.

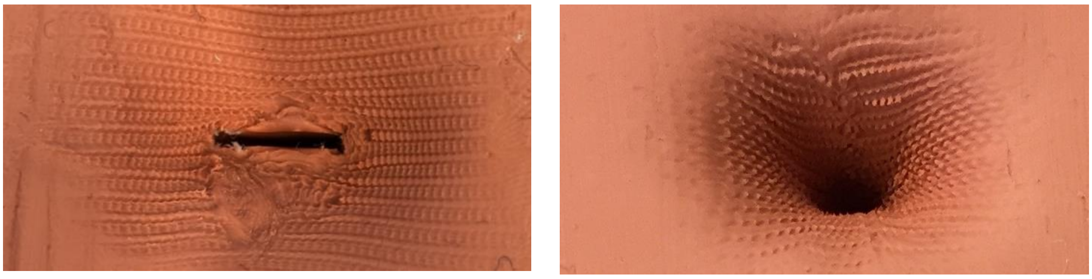


Figure 2. Cuts in plasticine, left panel: p-aramid as tested fabric, right panel: PBO as tested fabric.

To avoid this phenomenon in further fabrics, both filaments were used together in a spacer fabric. With the same machine properties two variations of the earlier-made spacer-construction were produced, where the spacer- and the loop-construction were made of either the aramid or the PBO-yarn, expecting them to compensate their counterparts' weak points, such as a deep crater.

2.2. Testing

The stab resistance of the different knitted fabrics was examined according to the standard of the Association of Test Laboratories for Bullet, Stab or Pike Resistant Materials and Construction Standards (VPAM 2011 [7]). According to this standard, protective gear is divided into different classes of protection. In protection class K 1 three tests with an impact-energy of 25 joule are run, in which every measured penetration depth must be less than 20 mm. This testing method checks textiles by letting a predefined blade with a predefined weight fall without braking out of a predefined height down onto the test-substrate, which is positioned on a plasticine-filled waggon. The weight onto which the blade is mounted is guided by two rail-bars, to ensure an impact in the right angle. It is fundamental, that the rail-bars guide the weight without decreasing its speed howsoever. The inner part of the waggon measures 350 mm x 400 mm x 150 mm. The ballistic putty has to be inserted in a way that prevents air-bubbles. Prior to every testing-session it has to be stored at a constant temperature that deviates by ± 2 °C at the most. The room temperature is stated at 20 °C (± 2 °C). The to-be-tested textiles should rest at least 12 hours at the same room temperature as well as at the relative air humidity of 65% (± 5%), which is the norm-climate. In order to test also thinner fabrics reliably, the falling height was reduced to 10 and 30 cm. To provide comparable results, the different fabrics were tested with varying numbers of layers to assure that their thickness would not differ much.

Table 1. Overview of yarns and the knitted structures produced from them.

Yarn parameters	Structures	Fabric thickness	Numbers of layers / overall thickness
Para-aramid Type 2040, 550 dtex	French weave-knit	2.62 mm	3 = 7.86 mm
	Interlock	2.73 mm	3 = 8.18 mm
	Milanese	2.66 mm	3 = 7.98 mm
	Spacer fabric	1.91 mm	4 = 7.64 mm
Zylon AS, 555 dtex	French weave-knit	2.03 mm	4 = 8.12 mm
	Interlock	3.58 mm	2 = 7.15 mm
	Milanese	1,97 mm	4 = 7.88 mm
	Spacer fabric	1.85 mm	4 = 7.40 mm
Zylon & Para-aramide	Zylon as tuck	2.37 mm	3 = 7.11 mm
	Aramid as tuck	1.72 mm	5 = 8.60 mm

3. Results

Figure 3 gives an overview of the results of the stab resistance tests of different knitted structures comparing PBO and aramid at a falling height of 10 cm (2.46 joule). The lower the result, the bigger is the stab resistance. Putting the PBO and the aramid knitted fabric to scale, the PBO always shows better results. The lower penetration depth of the PBO fabrics is significant in French knit-weave (PBO = 14.9 mm and aramid = 21.25 mm), Milanese (PBO = 12.79 mm and aramid = 22.18 mm) and spacer-fabric (PBO = 11.19 mm and aramid = 18.04 mm). The PBO and the aramid spacer fabrics have the best stab resistance results of all tested combinations (PBO = 2.47 mm and aramid = 2.7 mm).

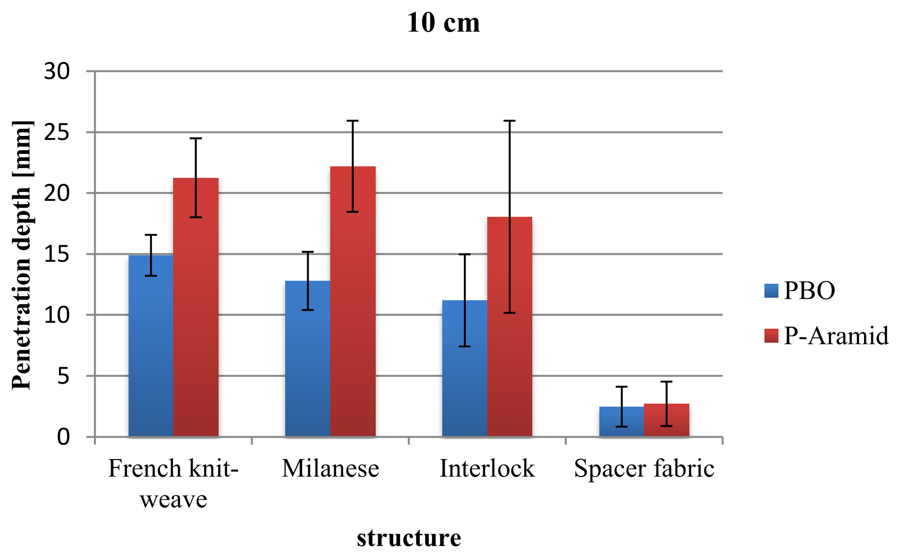


Figure 3. Comparison of the penetration depth of different knitted structures made of PBO and p-aramid (falling height: 10 cm).

Figure 4 shows the results of the same test and the same materials but with a falling height of 30 cm, which corresponds to an impact energy of 7.38 J. Again, the fabrics made of PBO achieve better results than the aramid fabrics. Only for the spacer fabric made from PBO the better result is significant (PBO = 12.03 mm and aramid = 19.52 mm).

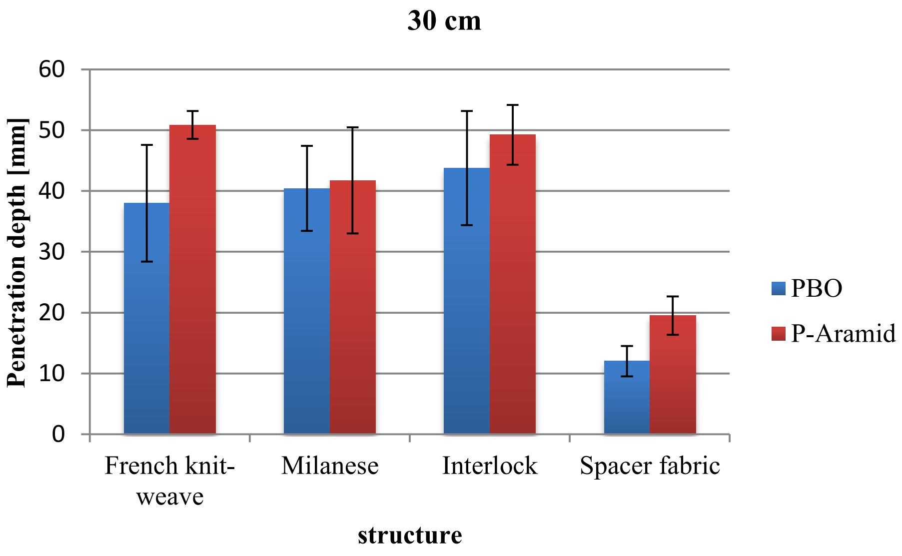


Figure 4. Comparison of the penetration depth of different knitted structures made of PBO and p-aramid (falling height: 30 cm).

Since the spacer fabric showed the best results in every comparison, figure 5 now puts the different material combinations to scale, but with the same knitted structure and with a falling height of 10 cm. The PBO fabric (2.47 mm), the aramid fabric (2.7 mm) and the PBO fabric with aramid used as tucks (2.83 mm) are showing almost the same stab resistance performance. The combined spacer-fabrics show a huge difference in their performance, since the data of the one with aramid used for the tucks is near its counterparts made of only one material while the construction that used PBO for the tucks has a remarkably higher penetration depth (10.66 mm). The craters of the combined spacers appeared lower than their PBO-counterpart as expected. Since this fact did not show any impact on the performance concerning the stab resistance, that was not yet investigated any further.

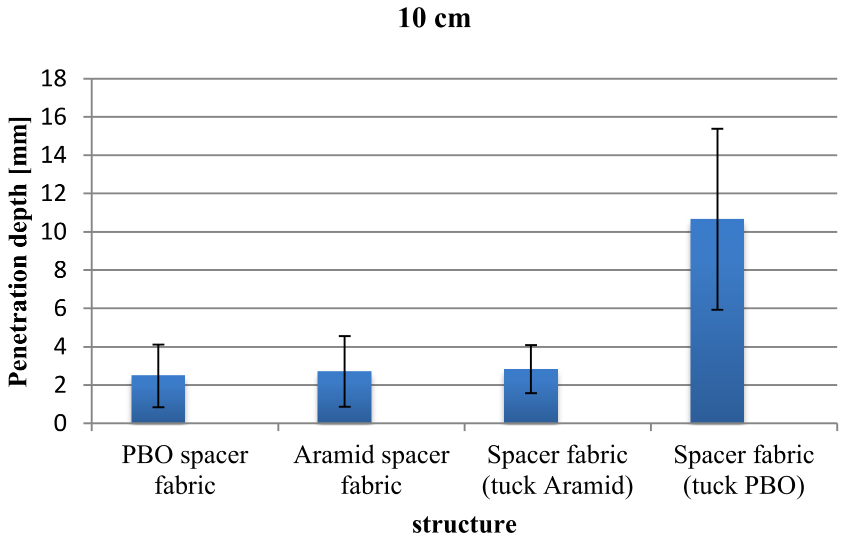


Figure 5. Comparison of the penetration depth of different spacer fabrics made of PBO and p-aramid (falling height: 10 cm).

Figure 6 shows the same fabrics as figure 5 only with an increased falling height of 30 cm. In this case the spacer-fabric made of both aramid and PBO with aramid used in the tucks shows the best resisting-performance (10.68 mm). Regarding the standard deviation, the stab resistance of the PBO with aramid in the tucks is in the same area as the PBO spacer fabric (12.04 mm). Both have a better performance than the aramid spacer fabric (19.52 mm). The combined spacer-fabric that uses PBO for the tucks has similarly insufficient results (26.16 mm) as in figure 5.

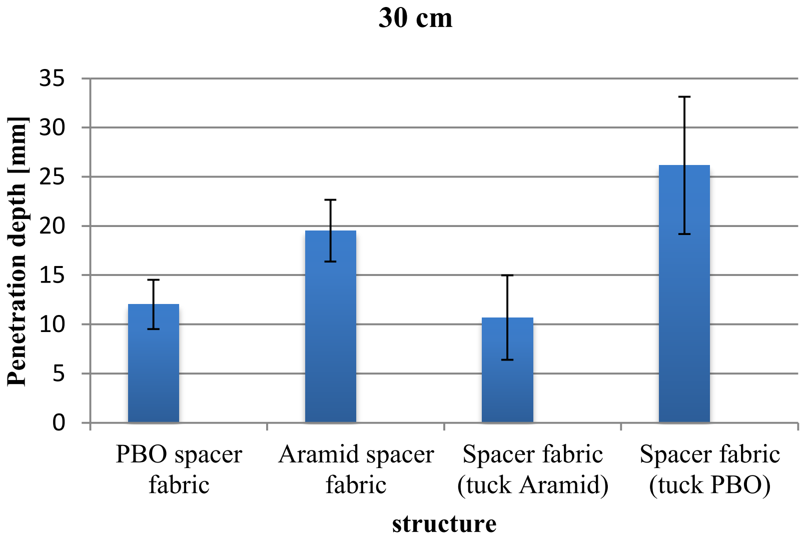


Figure 6. Comparison of the penetration depth of different spacer fabrics made of PBO and p-aramid (falling height: 30 cm).

Due to the inhomogeneous structures of knitted fabrics, the test results have relatively high standard deviations. The spacer fabric made from PBO has the lowest standard deviation which can be attributed to the fact that its structure is more even and stable (Figure 1).

4. Conclusion and Outlook

After having revisited numerous combinations of material- as well as construction-parameters the spacer-fabrics made of single PBO and PBO with aramid used as tucks seem to be the most promising. There will be further tests on material combinations, starting with combining PBO and UHMWPE in a spacer fabric, as well as spinning the three materials together and using the out-coming yarn for the structures mentioned above. Additionally new constructions will be tested with the PBO-fiber to decrease the flexibility of the single loops, so that the blade can be caught more easily. Last but not least there will be run further tests on the PBO-spacer fabric used above, such as martindale and washing-tests to ensure its suitability for the use in protective garments. To assure a better comparability and to minimize the craters the upcoming fabrics will be tested on top of a non-woven, which is the testing manner of the HOSDB, which provides the standard for body armor for the UK police.

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