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Stab-resistant Property of the Fabrics Woven with the Aramid/Cotton Core-spun Yarns

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Abstract: Aramid fibers are mainly used for industrial applications and human body protection against ballistic threats. But they are used mostly in forms of composites. And fabrics woven with a high yarn count offer a moderate protection performance against the knife stabbing due to the low shear strength. This research is focused on investigating the effect of the aramid core-spun yarns on the stab resistance of the woven fabrics. With the aramid core-spun yarns with core to sheath weight ratio of 1 to 2.5 the armor specimens having different fabric densities were prepared and the knife edge impact test was conducted. On the impact energy of the knife at the level 1 according to the NIJ standard, the drop tower test results demonstrated that fabric density of the armor specimens affected the stab resistance significantly. The penetration depth of the impactor through the armor specimens was associated with the thickness and mass of the armor sample in different ways. Being the stab resistance introduced by considering the penetration depth of the impactor via thickness and weight per surface area, the effects of the fabric conditions on the anti-stabbing property could be systematically analyzed and turned out that there was an optimal level of the fabric density, showing the most effective stab resistance.

Keywords: Aramid fibers, Body protection, Stab resistance, Core spun yarns, Fabric density, Knife stabbing, Penetration depth, Thickness, Mass

Introduction

Body armor material has conventionally been used to protect people against ballistic threats. The material can be characterized by high toughness and low weight, that is, high tenacity and high modulus. Anti-bullet material should have in addition the thermal stability against the instantaneous generation of collision heat, when a fast flying bullet collides with the body armor. The main factor that acts on the body protection is kinetic energy. However, the body armor for stab protection must have some different properties from that for the bullet protection. The impactor has a relatively low speed, that's, no generation of collision heat, but the armor breaks by the sharpness of the tip or the edge of the intruding object, mainly by the shear deformation of the armor.

Stab threats can be classified into two categories: puncture and cut. Puncture refers to the penetration of an object with pointed tips through a target, such as ice picks or awls. Cut refers to the destruction of the target with a continuous sharp edge like the knife edge. Cutting by knife edges is generally more difficult to stop than puncture, since the cutting edges cause a critical action giving rise to a continuous damage to the target during the stabbing.

Stab-resistant materials are available in various forms. Metal ring mesh (also called "chain mail") is used for the cut protection in commercial applications such as meat packing, and frequently incorporated into stab-resistant vests. The ring meshes, however, do not have the puncture resistance. Titanium foil is another design for both puncture and cut resistance. They are, however, fairly heavy and offer little ballistic resistance. Rigid metal, ceramic, or composite plates are also used for stab-resistant body armor. These rigid armors can offer an excellent stab resistance but are bulky and inflexible, making uncomfortable to wear them or difficult to hide for transportation.

Recently, fabrics woven with aramid yarns of a high yarn count (such as Kevlar Correctional^{TM}, DuPont Company) have been developed to provide specially a stab resistance against the spike threat. However, these high yarn count fabrics are expensive and offer just a moderate protection performance. Aramid fabrics coated with a thermoplastic resin are being used in commercial body armor systems to provide an improved protection performance against both the knife and the spike.

There have been many trials to apply the textile structure for the body protection again the stabbing. Suffice to take a few of them, Anctil *et al.* [1] reported on the stab performance and ballistic data for a series of fabric armor specimens. Gadow and Niessen [2] showed that aramid fabrics with thermal-sprayed ceramic coatings increased the energy absorption in a quasistatic stab test. Flambard and Polo [3] used even knitted fabrics as the basic textile structure for improving stab resistance. Ankerson *et al.* [4] measured the quasistatic stab resistance of pigskin and a synthetic skin simulant.

Confining the anti-stabbing action to puncture, Nguyen *et al.* [5] used clamped rubber membranes and a conical puncture probe to study the penetration and analyzed the membrane deformation and puncture force. Russell *et al.* [6] used a flat-

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faced puncture probe to measure the puncture resistance of clamped, non-woven, high modulus polyethylene fabrics.

Studies on the quasistatic cut resistance of fabrics and other thin materials also have been reported. Specifically, investigations into cutting properties of polymer sheets were conducted to explain the sophisticated fracture and friction during the cutting process for monolithic, visco-elastic materials [7-9]. Lara *et al.* [10,11] presented cut properties for specific fabric and film materials.

The requirement that the body protection armor should satisfy is not only confined to the mechanical resistance against the stabbing which was the major interest of the researches so far. The wear comfort is also an important factor that should be considered as well, for example the lightness, the flexibility, and the skin feeling while wearing the body armor.

In this paper, we research on the stab resistance of the fabrics woven with the armid core-spun yarns on the purpose of improving the wear comfort of the body protection armor and at the same time to achieve a good protection performance against stabbing threats, while the information on the relationship between the fabric density and the stab resistance is provided. To realize the intention of this research we prepared aramid core spun yarns and produced fabrics woven with various fabric densities. And applying a test method, NIJ standard, to test the fabric performance for stab protection, the penetration depth of the impactor through the armor specimen was measured so that the relationships between the stab resistance and the armor thickness or the mass for various fabric densities were established.

Experimental

Materials

To prepare the aramid-core spun yarn, we used cotton staples and aramid filaments. In a ring spinning machine equipped with a filament feeding device the filaments were placed in the center of the yarn, while the cotton staples wrap the filaments. The specifications of the filaments and staples are given in Table 1. Table 2 presents manufacturing conditions of aramid core-spun yarns.

Table 1. Specifications of the filaments and staples

	Sheath-staples	Core-filament
	Cotton	p-aramid (Twaron)
Thickness (tex)	400 (in roving)	22.2 (133 filaments)
Fiber length in average (mm)	31.5	Endless

Table 2. Specifications of the aramid core-spun yarn

Weight ratio (core filament : sheath-staples)	1:2.5
Twist (T.P.M.)	370
Yarn thickness (tex)	Single strand: 77.7 Two plied strand: 168
Process speed (mm/min)	4.3

Since the single aramid core-spun yarn has a property to create snarls due to the residual unbalance of the torque that prohibit a continuous weaving process, two strands were plied to a strand to eliminate the snarls. The single aramid core-spun yarn and the two-plied yarn are shown in Figure 1.

In the weaving process, we inserted two wefts in a picking

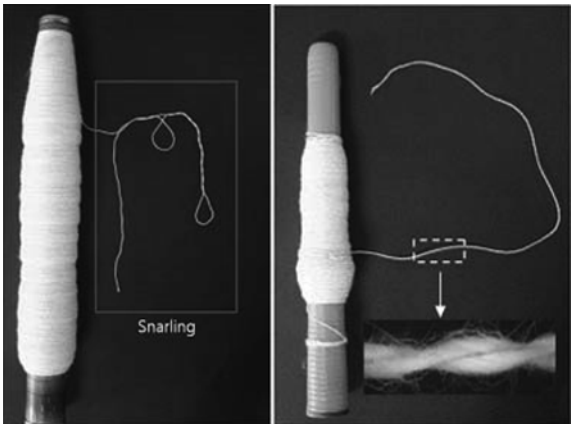
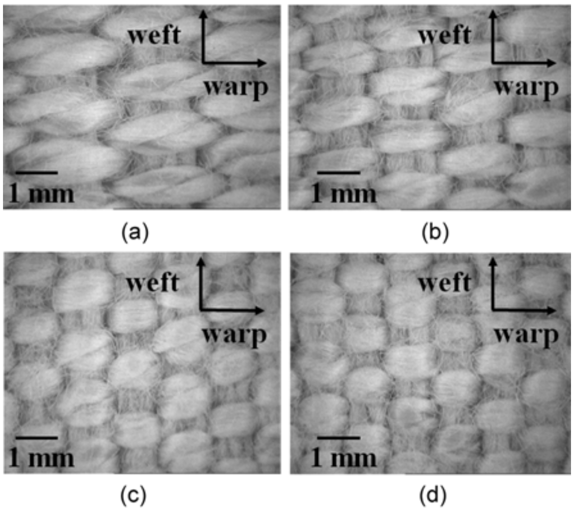


Figure 1. Single aramid core-spun yarn and two-plied aramid core-spun yarn.

Table 3. Specifications of the armor fabrics woven with the aramid core-spun yarns

Warp density (ends/cm)	16.4			
Weft density (picks/cm)	4.2	6.3	8.4	9.7



(a) (b) (c) (d)

Figure 2. Photographs of the woven fabrics with aramid core-spun yarns; (a) 4.2 picks/cm textile, (b) 6.3 picks/cm textile, (c) 8.4 picks/cm textile, and (d) 9.7 picks/cm textile.

motion, because the warp yarns were two plied. The fabric pattern was plain for all the specimens. During the weaving we kept the warp density constant. But the fabric weft density was changed with 4 levels to study the stab resistance with respect to the fabric density. The fabric specifications are given in Table 3. And the fabric specimens prepared in the weaving process are displayed in Figure 2.

Testing Method

The stab test was performed utilizing the conventional drop tower as suggested by the National Institute of Justice (NIJ), a standard for stab testing frame of protective armors [12]. This method uses a drop mass with standardized blades, which is then dropped onto an unclamped fabric placed on top of a damped backing material. The mass, speed, and damping characteristics of the backing material for the experiment have been designed to mimic the biomechanical process of stabbing assaults [13-15].

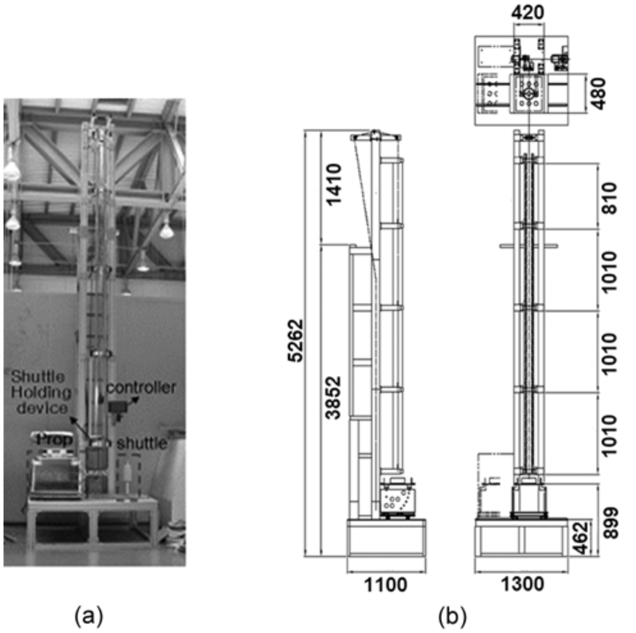


Figure 3. Experimental system to check the stab resistance properties; (a) photograph and (b) dimensional specifica.

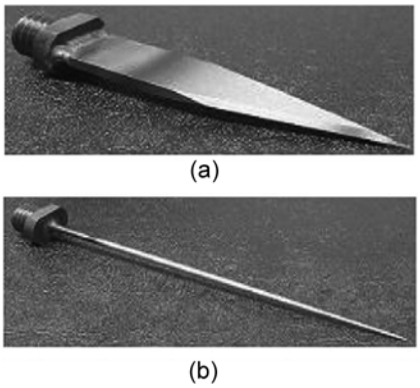


Figure 4. Stabbing impactors for stab test; (a) knife and (b) spike.

Figure 3 shows drop tower system that we used. Two types of impactors that NIJ recommends are the "S1" knife, and the "spike", as illustrated in Figure 4.

For the stab testing the impactor was grabbed by a carrier and mounted to a cross-head in a rail-guided drop tower, while the stab target was placed on a multilayer foam backing (Figure 5). This backing material consisted of four layers; a multi-layered neoprene sponge layer, each layer of which is 5.8 mm thick, followed by 31-mm-thick polyethylene foam layer that was backed by two 6.4 mm thick layers of rubber. Synthetic witness papers, Polyart^{TM}, were inserted under the target and between each layer of neoprene sponge. In this research the backing system was slightly modified to obtain more information on the penetration depth according to the specimen specifications: the neoprene sponge thickness of 6 mm, and six layers of the neoprene sponge.

To perform a stab experiment, the impactor mounted on the cross-head was loaded with a weight so that the potential energy of the cross-head was constant with the level 1 (E1=24J) according to the NIJ standard, when it was dropped from a fixed height to the specimen. The depth of penetration into the target was quantified in terms of the number of witness paper layers penetrated by the impactor.

Specimens were prepared by stacking fabrics with a fabric density, while changing the folding number of the fabrics. And various specimens were produced with various levels of fabric densities. In stab testing the specimens of size 35×40 (cm^2) were clamped by nylon straps and the sharpness of the impactor was monitored and controlled by using a modified hardness tester as described by the NIJ standard. Table 4 shows the conditions for the drop tower testing.

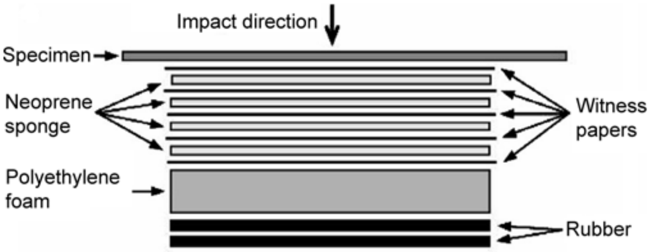


Figure 5. Construction of the foam backing system for stab test.

Table 4. Conditions for drop tower testing

"E1" strike energy (Protection level 1)	24±0.50(J)
Shuttle weight (Drop mass)	1.8 (kg)
Drop knife type	Blade (S1), Spike
Drop height	1,370 (mm)
Theoretical impact speed	5.1 (m/s)
Dimension of the specimen	35×40 (cm^2)

Preliminary tests indicated that it was difficult to set a relationship between the penetration dept and the number of layers, when a spike as an impactor was used for woven fabrics. The spike has such a slim shape that it pierced easily through the backing system, once it stroke the specimen. If the spike could not pierce the sheets of the fabrics, it usually sprang back out of the backing. Therefore, we only used spikes to test the specimen in a provisory way, that is, to see if the knife "S1" could penetrate the specimen more deeply than 7 mm, the distance the NIJ standard allows for the knife "S1" to penetrate for body protection.

Results and Discussion

The knife edge impact on the body protection armor brings out damages or fractures of the specimen that can be delineated in terms of the penetration depth and the number of fabric layers. The drop tower test results are illustrated in Figure 6 for the fabrics woven with the aramid core spun yarns with four levels of the fabric density. As the number of layers increases, the impact energy is more absorbed by the armor specimen so that the penetration depth of the impact knife into the backing material decreases. A higher fabric density leads to a less penetration depth. But there is no significant difference in the penetration depth in the vicinity of critical protection depth between 5 and 10 (mm), if the weft fabric density is higher than 8.4 (picks/cm).

The relation between the penetration depth and the number of layers of the armor fabric specimen is needed, if the number of layers in a specimen appropriate to a penetration depth is to be estimated. This relationship can be obtained by curve-fitting the measured data. Within the range of the penetration depth and number of the specimen layers in this work, a 2nd powered approximation showed a good result. With y as the penetration depth of the impactor and x as the number of the layers in the specimen, this relationship can be described as follows;

Table 5. Parameters fitted to a 2nd powered curve for the penetration depth and number of layers (aramid hybrid armor fabrics)

Fabric density (picks/cm× ends/cm)	Penetration depth (y) *vs*. number of sheets (x) ($y=a\cdot x^2+b\cdot x+c$)		
	a	b	c
4.2×16.4	-0.088	1.050	32.610
6.3×16.4	-0.062	-0.968	47.513
8.4×16.4	-0.469	8.024	-1.179
9.7×16.4	-0.356	5.530	9.464

$$y = a\cdot x^2 + b\cdot x + c \quad (1)$$

where a, b, c are the parameters.

Table 5 displays the parameters attained from the approximation to a 2nd powered curve by the curve-fitting method.

To have a general view for the sheath effect on the stab resistance of the armor fabrics by comparing the hybrid yarn fabrics with the pure aramid fabrics, the stab test was conducted for the specimen made of the pure aramid yarns, while the same aramid filaments were used as those for the core spun yarns. Figure 7 shows the results.

Since the pure aramid filament yarn had no sheath staples, the yarn thickness, that is, the linear density, was 1/3.5 of the hybrid yarns. Even though the fabric density was the same, the size of the pores in the pure aramid fabrics became bigger than that of the hybrid specimens. The penetration took place easily so that more layers of the pure aramid fabrics were required to reach at the same penetration depth as the hybrid fabrics. The comparison of the test results for

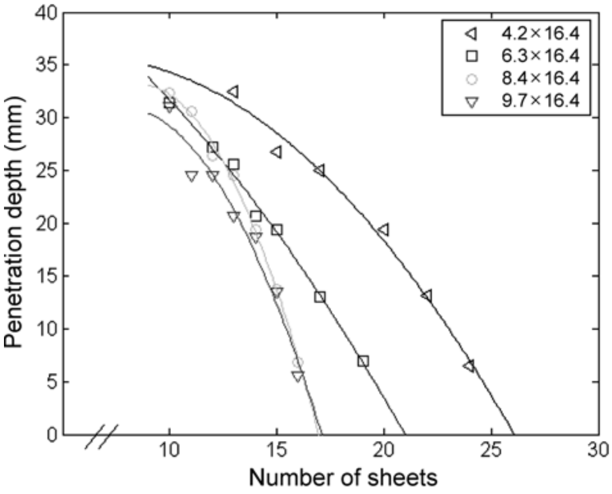


Figure 6. Knife-edge impact resistance of the specimens with the core spun yarns according to the number of layers.

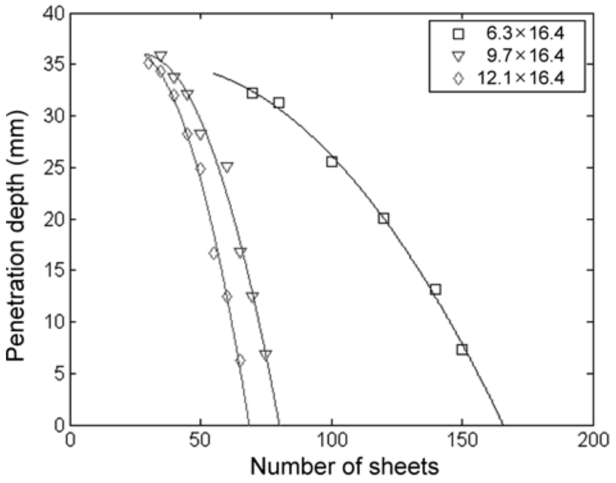


Figure 7. Knife-edge impact resistance of the specimens with the pure aramid yarns according to the number of layers.

Table 6. Parameters fitted to a 2nd powered curve for the penetration depth and number of layers (pure aramid armor fabrics)

Fabric density (picks/cm × ends/cm)	Penetration depth (y) *vs*. number of sheets (x) ($y=a\cdot x^2+b\cdot x+c$)		
	a	b	c
6.3×16.4	-0.002	0.134	32.815
9.7×16.4	-0.013	0.741	25.628
12.1×16.4	-0.018	0.841	26.489

the weft fabric densities of 9.7 and 12.1 (picks/mm) doesn't show so much difference as between 6.3 and 9.7 (picks/mm), which indicates also that the fabric density plays a role in the stab resistance of the woven fabrics. These results also could be expressed in terms of a 2nd powered curve by the curve fitting. Table 6 displays the parameters of the curve fitted 2nd power function for the pure aramid armor fabrics.

Penetration Depth and Thickness of the Specimen

The fabric density influences the surface thickness of fabrics. The relationship between the penetration depth and fabric thickness was displayed in Figure 8. The aramid hybrid fabrics with weft density of 6.3 (picks/cm) or more have a similar anti-stabbing behavior with respect to the fabric thickness, showing a steeper gradient than 4.2 (picks/cm) weft density fabric. If the penetration depth has to be, for example, under 7-mm, the armor fabrics with weft fabric density of 8.4 (picks/cm) can be most efficient among the specimens from the thickness point of view.

The relation between the penetration depth and specimen thickness can be obtained by the curve-fitting. Within the range of the penetration depth and the specimen thickness, this work revealed a good approximation to a 2nd powered function. Table 7 gives the parameter values obtained from the approximation to a 2nd powered curve.

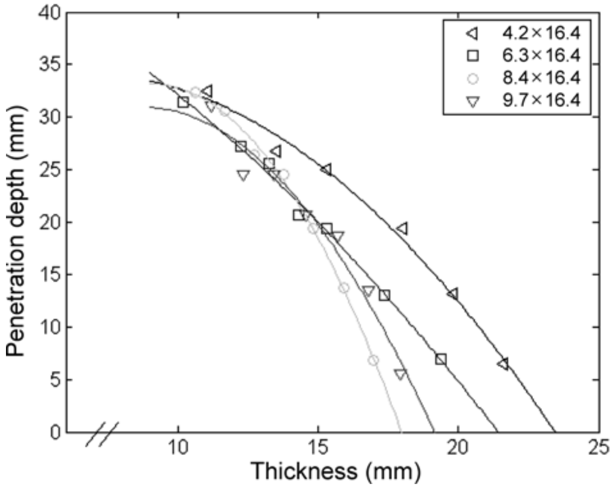


Figure 8. Knife-edge impact resistance of the specimens with the core spun yarns according to the thickness.

Table 7. Parameters fitted to a 2nd powered curve for the penetration depth and thickness of the aramid hybrid armor fabrics

Fabric density (picks/cm × ends/cm)	Penetration depth (y) *vs*. thickness (x) ($y=a\cdot x^2+b\cdot x+c$)		
	a	b	c
4.2×16.4	-0.117	1.490	29.512
6.3×16.4	-0.059	-0.949	47.513
8.4×16.4	-0.417	7.570	-1.179
9.7×16.4	-0.284	4.937	9.464

Penetration Depth and Weight of the Specimen

Weight of the personal body armor is an important factor, because the armor fabrics must be put on for a while during an activity. Therefore the surface density should be taken into consideration. Figure 9 illustrates the relationship between the penetration depth and the areal density of the armor fabrics. A lower areal density leads to a deeper penetration of the impactor through the specimen. The difference in the anti-stabbing behavior with respect to the areal density of the specimen, however, hardly looks significant in the different fabric density. Nonetheless the specimen with weft fabric density of 8.4 picks/cm shows the steepest gradient, which indicates that the penetration depth is the most sensitive to the mass.

But the specimen with 6.3 picks/cm weft density has the smallest surface density among the specimens, if the penetration depth may be allowed to exceed 7 mm. This result indicates that thickness and areal density of the fabrics affect the penetration depth in a different way through the fabric density, if Figures 8 and 9 are compared.

The relationship between the penetration depth and areal density of the specimen could be expressed very good in the form of a 2nd powered approximation curve, the results of which are given in Table 8.

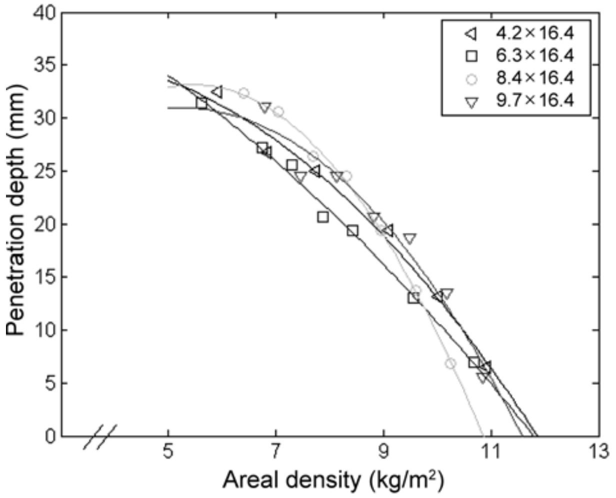


Figure 9. Knife-edge impact resistance of the specimens with the core spun yarns according to the areal density of the armor specimen.

Table 8. Parameters fitted to a 2nd powered curve for the penetration depth and areal density of the aramid hybrid armor fabrics

Fabric density (picks/cm× ends/cm)	Penetration depth (*y*) *vs*. areal density (*x*) ($y=a\cdot x^2+b\cdot x+c$)		
	a	*b*	*c*
4.2×16.4	-0.426	2.308	32.610
6.3×16.4	-0.195	-1.722	47.513
8.4×16.4	-1.145	12.537	-1.179
9.7×16.4	-0.774	8.156	9.464

Stab Resistance

Viewed from the results obtained so far, the experiment shows that the specimen with 8.4 picks/cm seems to be the most effective and suitable for the anti-stabbing; the lowest values of thickness and areal density of the armor specimen, which can be assured in Figures 8 and 9. However, the anti-stabbing property of the specimens cannot be interpreted with consistency, because the thickness and weight of the armor fabrics have different influence on the penetration depth.

To express the property that corresponds to the resistant performance of the armor fabrics against the knife edge impact, a quantitative measure needs to be defined while those factors are taken into account, so called the stab resistance. Since the stab resistance can be considered as the ability of the armor fabrics to absorb the stabbing energy, we introduced a parameter that describes the energy absorption in terms of the penetration depth and the change of the penetration depth with respect to thickness and weight; that is, the thickness and areal density of the specimen at the penetration depth equal to zero, and the penetration slope with the thickness and areal density at the penetration depth equal to zero.

The greater thickness or areal density of the armor fabrics for the zero penetration depth implies the lower resistance against the stabbing. And a large change in the penetration depth for a small change in the thickness or areal density of the armor fabrics can be interpreted as the better resistance. Therefore stab resistance on the thickness, R_{Th}, is defined as

$$R_{Th} = \left[\frac{1}{Th}\right]_{at\ Pd=0} \cdot \left[\frac{\Delta Pd}{\Delta Th}\right]_{at\ Pd=0} \tag{2}$$

and stab resistance on the weight, R_W, is defined as

$$R_W = \left[\frac{1}{W}\right]_{at\ Pd=0} \cdot \left[\frac{\Delta Pd}{\Delta W}\right]_{at\ Pd=0} \tag{3}$$

where *Th*, *Pd*, *W* and *Th*, *Pd*, *W* are the thickness, the penetration depth, and the weight per surface area of the armor fabrics, respectively. Then, the total stab resistance, R_{Stab}, can be obtained by multiplying the stab resistance on the thickness, R_{Th} and stab resistance on the thickness, R_{Th};

$$R_{Stab} = R_{Th} \cdot R_W \tag{4}$$

Table 9 shows the test results obtained from the specimens, indicating that the stab resistance for the specimens prepared for this research changes according to the fabric specifications. It reaches a minimum value for the fabric density of 8.4 (picks/cm)×16.4 (ends/cm). This result implies that there is a fabric condition that provides the highest stab resistance.

Besides, the preliminary tests with spike had shown that all the specimens with 4 fabric densities were not pierced, if they were not pierced by the knife. This leads to the conclusion that the woven fabrics with armid core-spun yarns could protect the body against spike, if they are good for the knife “S1”.

Conclusion

In this research we tested the anti-stabbing performance of fabrics made of aramid core spun yarns that can have a good stab resistance and at the same time improve the wear comfort.

At first the core yarns were prepared with a given twist and a core-to-sheath weight ratio on a ring core spin system and the fabric specimens were produced, while the fabric density in weft was changed. In the preliminary tests with the spike impactor the specimens were selected that possessed the ability to resist against stab (knife and spike) threats; i.e., the weft fabric density in 4 different levels, while the warp fabric density was kept constant. Then the fabrics were stacked in various layers to anti-stabbing test specimens that were delivered to a drop tower tester. As impactor knife “S1” was used, and the impact energy level of E1 (E1=24J) was applied, as the NIJ standard-0115.00 specified.

The experiments turned out that the fabric density influenced strongly the anti-stabbing property. As the armor

Table 9. Stab resistance of the armor fabrics woven with aramid/cotton core-spun yarns

Fabric density (picks/cm×ends/cm)	No. of sheets	Th at *Pd*=0 (*mm*)	*W* at *Pd*=0 (kg/m^2)	*Pd* slope via *Th* at *Pd*=0	*Pd* slope via *W* at *Pd*=0 (mm/(kg/m^2))	R_{Stab} (1/(kg/m^2)^2)
4.2×16.4	24	23.4	11.9	-4.0	-7.8	0.11
6.3×16.4	19	21.4	11.8	-3.5	-6.3	0.09
8.4×16.4	**16**	**18.0**	**10.9**	**-7.4**	**-12.3**	**0.46**
9.7×16.4	16	19.1	11.6	-5.9	-9.8	0.26

thickness or weight increased, the anti-stabbing performance got improved, however in a different way. There was a most efficient and suitable range of the fabric density that offered the best resistance against knife impact, decided by a parameter that was defined by the thickness and areal density of the armor fabrics in terms of penetration depth.

Under the experimental conditions, specifically, given the weight ratio of aramid core to cotton sheath of 1:2.5, and the warp fabric density of 16.4 ends/cm, the fabric specimen with 8.4 picks/cm weft density showed most advantageous stab resistance; it had the smallest thickness and weight to resist the penetration of the knife edge impactor through the armor fabrics.

Acknowledgement

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