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Evaluation of Anti-stabbing Performance of Fabric Layers Woven with Various Hybrid Yarns under Different Fabric Conditions

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Abstract: Various types of special fibers are used for human body protection, mostly in the form of fiber-reinforced composites. These composites are made of special fibers and matrix resin; however, they are often not comfortable for the wearer due to the lack of flexibility and air permeability. This study focuses on an evaluation of human body protective performance against stabbing for various special fibers such as aramid, basalt, and steel fibers, being utilized in cotton hybrid forms. These hybrid forms are designed to improve wearer comfort, while maintaining adequate anti-stab resistance. Specimens prepared with various fabric densities are tested in terms of anti-stabbing performance, according to the NIJ standard. In addition, we investigate the influence of factors such as fiber type, the number of fabric layers, fabric weight, and fabric density on anti-stabbing performance. Results show that the penetration depth of the impactor, which punctures and protrudes through the specimens, decreases with the number of layers, the thickness, and the mass of the armor sample; however, these factors have different relationships according to the material type. Consequently an objective evaluation of anti-stabbing performance is needed. We suggest an anti-stabbing index that can be applied as a criterion to evaluate the anti-stabbing performance of various specimens woven with special fibers under different fabric conditions. Using the new index, anti-stabbing performances of various specimens can be compared and raw material and fabric conditions that offer the most efficient anti-stabbing performance can be selected.

Keywords: Body protection, Stabbing, Special fibers, Hybrid form, Fabric density, Fabric layers, Impactor, Drop tower test, Anti-stabbing index

Introduction

For human body protection, various types of composites are used, reinforced with either special high tenacity fibers or with a pliable two-dimensional textile structure. Personal body protection can be divided into two groups according to the protection object, namely, that against a kinetic impact and that against the intrusion of a sharp edge. The former refers to cases involving bullets, while the latter refers to stabbing with swords, knives, or other sharp objects. In modern manufacturing industries in which products' constituent components must be finished using thermal, mechanical, or chemical treatments, workers are exposed to various threats from objects with sharp edge. An increase in international threats and violence also makes stab protection critical for those who work in potentially life-threatening environments in which a wide range of protection is required. Moreover, people in everyday situations are increasingly exposed to dangers from sharp-edged objects. Therefore, research into body protection against stabbing has garnered more attention in terms of safety in not only working conditions, but also in everyday life.

Body protection is an old issue in technological development, especially in terms of body armor developments for military or public enforcement purposes. Metal rings, metal fish scales, and leather plates are traditional forms of body armor structures. Since Du Pont's development of Kevlar™, numerous forms of body armor have been introduced, utilizing different fiber reinforced composites. Recently much research has focused on the abilities of fabrics to protect the human body. Anctil *et al.* [1] reported body protection data for a series of armor fabrics, and Gadow and von Niessen [2] treated aramid fabrics with ceramics, showing an increased absorption of impact energy. Termonia [3] contributed to the development of a model showing needle penetration through the fabric system, concluding that the fabric friction against the conical needle after puncture imposes a maximum force on the needle during puncture. Russell *et al.* [4] introduced experimental results for the puncture resistance of HMPE hydro-entangled fabrics, and Joo and Kang [5] developed a theoretical model for multi-plied fabric deformation under impact, considering various fabric features, and Joo *et al.* [6] further analyzed the impact deformation of 3D braided composites and fabric composites.

Research analyzing body protection against stabbing has also been conducted. Blyth and Atkins [7] studied the stab resistances of thin metal sheets, Shedden *et al.* [8] modeled the stabbing mechanism, and Ankerson *et al.* [9] measured the quasistatic puncture resistances of pigskin and a synthetic skin simulant. Lara and Masse [10] evaluated the cutting resistance of clothing materials. For industrial purposes quasistatic puncture resistance was studied by Erlich *et al.* [11] using Zylon™ fabrics for turbine blade containment, applying both chisel-nosed and sharp-edged penetrators.

All of this research focused on fabrics woven with neat high tenacity fibers or resin-treated woven fabric, which

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protect from damage against a rapidly intrusive projectile or stabber. Resin-coated or laminated fabrics are, however, inconvenient for the wearer. The flexibilities of the fabrics are low, and the surface features are not suitable for clothing. Furthermore, the heat radiated from the human body and the humidity generated by body motion cannot be easily ventilated, or absorbed by these fabrics. From this view point there was recently a research conducted by Duong *et al.* [12] investigating the stab-resistant property of multi-layered fabrics made of aramid filament-cored and cotton wrapped compound yarns, while the concept of stab resistance was introduced.

In this study, woven fabrics made of special fibers were considered as the basic material for body protection in the form of protective jackets or other clothing. The fabrics were made with threads of special fibers such as aramid, basalt, and steel fibers, in cotton hybrid forms, and were hypothesized to provide a solution for protecting the human body against stab threats, while, at the same time, improving wearer comfort. The stabbing penetration depth was tested to investigate the influences of factors such as the number of fabric layers, the fiber types, and the fabric density. We also suggest an anti-stabbing index that can be used as an evaluation criterion to compare the anti-stabbing performances of various materials.

Experiments

The Test Method

We adopted the stab resistance test method formulated by the National Institute of Justice (NIJ), the standard stab test for protective armors [13]. This method uses a drop mass with standard blades equipped with an impactor (Figure 1). The impactor can have different forms, including knives or spikes. This experiment employed the "S1 knife", as shown in Figure 2.

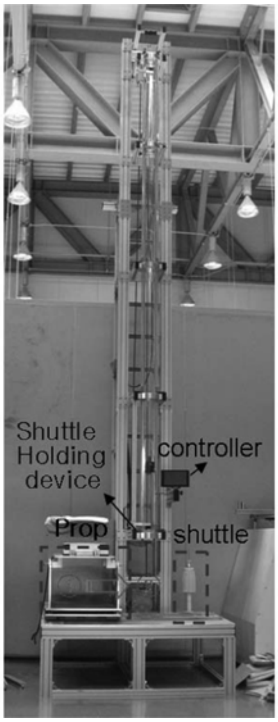

Figure 1. Anti-stabbing test equipment (drop tower type) according to the NIJ standard [12].

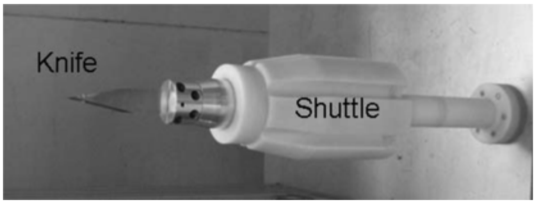

Figure 2. Stabbing impactor used for the stab test.

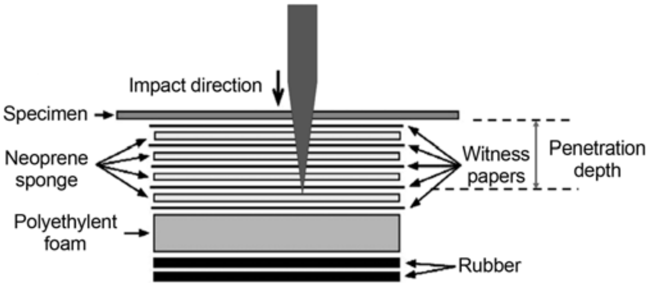

Figure 3. Construction of the backing system.

The knife, which is dropped onto an unclamped fabric placed on top of a damped backing material, has a level 1 impact energy (E1=24 J). The mass, velocity, and damping characteristics of the experiment were designed to mimic the biomechanics of a real stabbing assault.

The damped backing material that receives the stabbing impactor consists of four layers. The first layer is a multi-layered neoprene sponge layer, of which each layer is 5.8 mm thick. The second layer is a 31 mm-thick polyethylene foam layer, which is then backed by two 6.4 mm-thick layers of rubber. To measure the penetration depth of the impactor through the specimen, Polyart$^{\mathrm{TM}}$ synthetic witness papers were placed between each layer of the neoprene sponge below the target (Figure 3).

Materials and Specimens

The specifications of the filaments and the staples used in this research are given in Table 1. Aramid and basalt fibers were in the form of filaments, while metal fibers were staples. The sheath fibers for the core spun yarns or the covered yarns were cotton.

The hybrid yarn conditions for the armor specimens are given in Table 2. The core spun yarns for the aramid specimens had a core-to-sheath weight ratio of 1:2.5, while the metallic core spun specimens made use of the weight ratio of 1:1. The basalt specimens, however, were prepared so that the basalt filaments were covered with two strands of

Table 1. Specifications of the material used for the test specimens

Material		Fiber specifications
p-Aramid filaments		22.2 tex (133 fil)
Basalt filaments		50 tex (200 fil)
Metal staple yarn (stainless steel 316-L)		65 tex Mean fiber length: 150 mm Mean fiber diameter: 12 μm
Cotton	Rovings	2×400 tex Mean fiber length: 31.5 mm Micronaire value: 4.38
	Staple yarns	17.72 tex (2-plied)

Table 2. Specifications of the hybrid yarns

	Cored yarns		Covered yarns
	Aramid-cored hybrid yarn	Metal-cored hybrid yarn	Basalt filaments covered with two strands of two-ply cotton yarn
Core-to-sheath weight ratio	1:2.5	1:1	1:1
Twist (TPM)	200, S (380, Z)	184, Z (389, S)	
Linear density (tex)	168 (2 plied)	296 (2 plied)	99 tex

Table 3. Specifications of the armor fabrics

Specimens	Warp density (ends/cm)	Weft density (picks/cm)
Aramid hybrid (CA)	16.4	4.2, 6.3, 8.4, 9.7
Basalt hybrid (CB)	16.4	4.2, 6.3, 8.4, 9.7, 12.1, 13.2, 14.2
Metal hybrid (CM)	16.4	3.8, 4.5, 5.0, 5.6, 6.3

two-ply cotton yarn with a weight ratio of 1:1.

Table 3 details the specifications of the armor specimens. The fabric had a constant warp density of 16.4 ends/cm, while the weft density varied by level. Figure 4 shows the specimen surfaces prepared for this research.

Results and Discussion

Armor Fabric Strength

Figure 5 shows the test results in terms of the tensile strength per thickness of armor for the specimens made of aramid, basalt, and metal hybrid yarns with respect to the fabric density, which is represented in terms of the warp and weft contact point densities. Tensile strength is dependent on fabric density, and this dependency appears to be negative with respect to the fabric density; as the fabric density increases, the strength of the fabric specimens decreases. This indicates that the fabric thickness increase has less of an

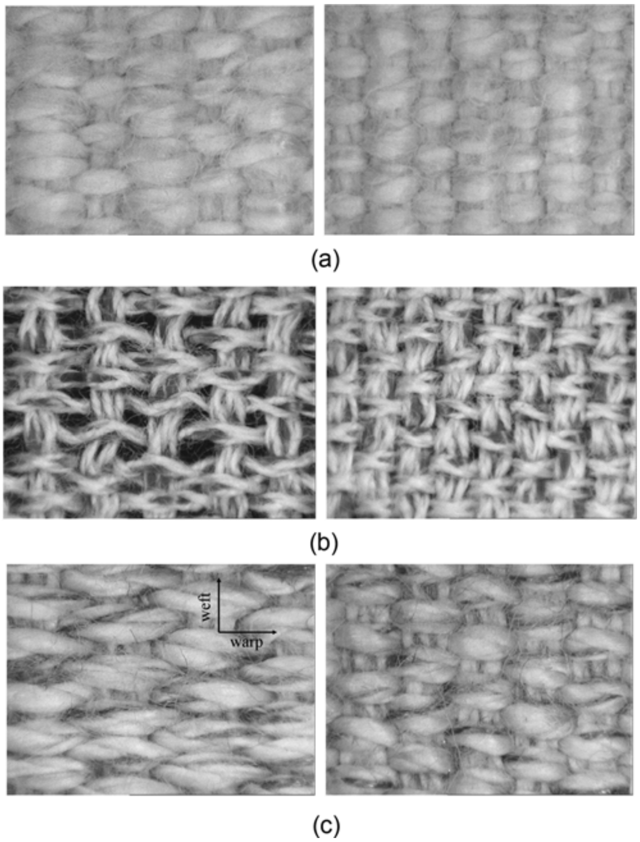

Figure 4. Photographs (×40) of the specimens; (a) aramid-cotton hybrid yarn fabric (CA) (left: 6.3 picks/cm×16.4 ends/cm, right: 9.7 picks/cm×16.4 ends/cm), (b) basalt-cotton hybrid yarn fabric (CB) (left: 6.3 picks/cm×16.4 ends/cm, right: 9.7 picks/cm×16.4 ends/cm), and (c) metal-cotton hybrid yarn fabric (CM) (left: 3.8 picks/cm×16.4 ends/cm, right: 6.3 picks/cm×16.4 ends/cm).

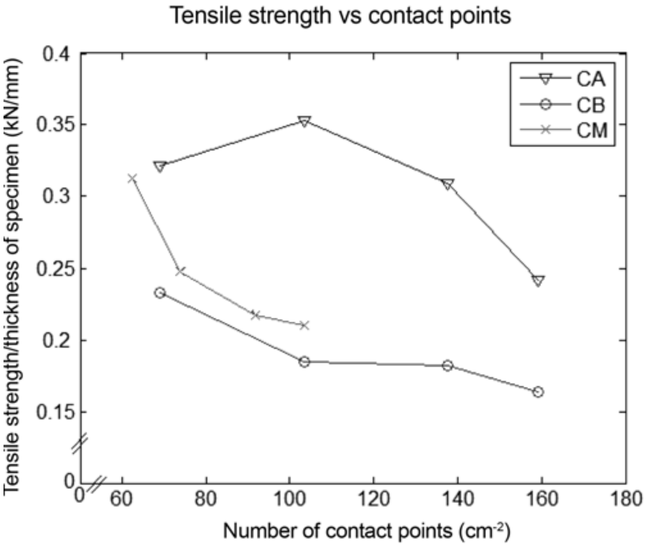

Figure 5. Tensile strengths per thickness of the specimens according to contact point density.

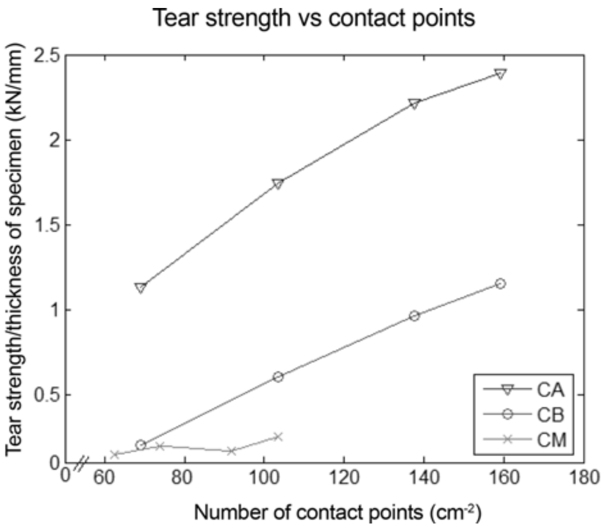

Figure 6. Tear strengths per thickness of the specimens according to contact point density.

impact on tensile strength than the fabric density increase does. Increased fabric density led to increased waviness in the core yarn fabrics, and the warp yarns became weaker due to increased shear deformation. Therefore, dense fabrics increased in thickness more rapidly than they increase in strength, resulting in a decreased strength per thickness measurement. The aramid specimen seemed to have the greater strength per thickness (Figure 5); however, aramid is not necessarily the most suitable material for body protection because the yarns have different finenesses.

A sharp edge or blade will cut the constituent yarns of the armor fabric during penetration, which can relate to the shearing properties of the yarn. In terms of the deformation of the planar structure, a stabbing action causes shearing deformation perpendicular to the surface. Therefore we conducted a tearing test, evaluating tear strength per thickness according to fabric density for aramid, basalt, and the metal hybrid yarns (Figure 6). The tear strength increased almost linearly with fabric density, except for the metal hybrid fabrics. This implies that the shear strength increased more rapidly than did the thickness when the fabric density increased. Therefore, the thickness of the armor fabric plays a very important role in anti-stabbing performance.

Therefore, the armor fabrics made of hybrid yarns of special fibers had decreasing tensile strengths per thickness but increasing tear strengths per thickness, as the fabric density increased. It is thus complicated to estimate or explain the effects of fabric density on stabbing performance from a perspective of mechanical strength. More information needs to be collected by testing the anti-stabbing stabbing performance of the fabric type body armor.

Stab Test

The stabbing action was simulated by an impactor drop, using the drop tower test method. Figure 7 details the specimens that were tested. When the stabbing impactor dropped, the specimen surface was destroyed, leaving the staples entangled in the surface, which may have influenced the stabbing resistances of the armor fabrics. For stab resistance analysis, we measured the penetration depth of the impactor through the specimen. The measured results were then analyzed to determine the exact effects of the parameters, such as the number of layers, the thickness, and the weight of the armor fabrics, while also considering the raw material and fabric density.

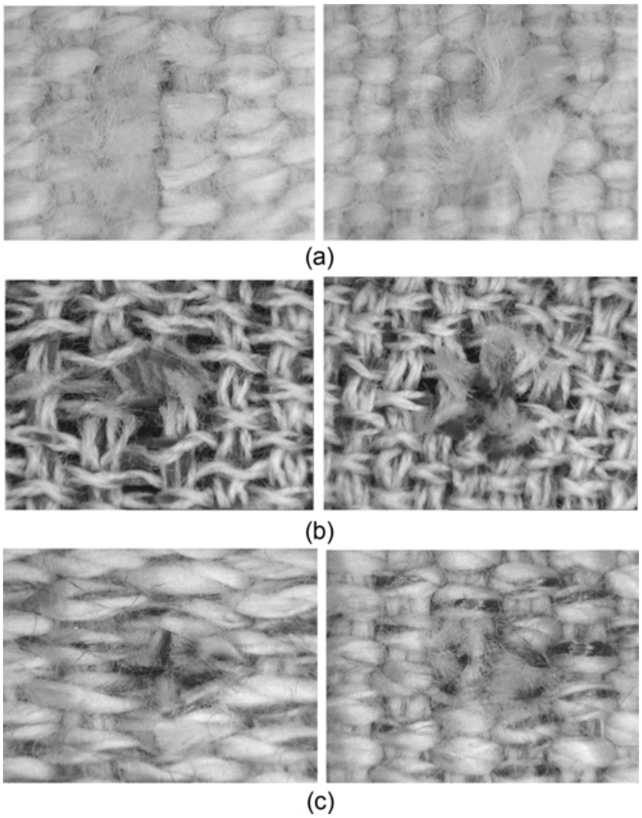

Figure 7. Photographs (×40) of the specimens penetrated by the stabber; (a) aramid-cotton hybrid yarn fabric (CA) (left: 6.3 picks/cm×16.4 ends/cm, right: 9.7 picks/cm×16.4 ends/cm), (b) basalt-cotton hybrid yarn fabric (CB) (left: 6.3 picks/cm×16.4 ends/cm, right: 9.7 picks/cm×16.4 ends/cm), and (c) metal-cotton hybrid yarn fabric (CM) (left: 3.8 picks/cm×16.4 ends/cm, right: 6.3 picks/cm×16.4 ends/cm).

Penetration Depth vs. Number of Layers

The penetration depth is defined as the distance between the bottom surface of the specimen and the front tip of the impactor which is drilled through the armor specimen. Penetration depth is closely related to the number of specimen layers and the fabric density, which are, in turn, influenced by the material. Therefore, the penetration depths of the prepared specimens using aramid, basalt and metal fibers were measured in the drop tower tester.

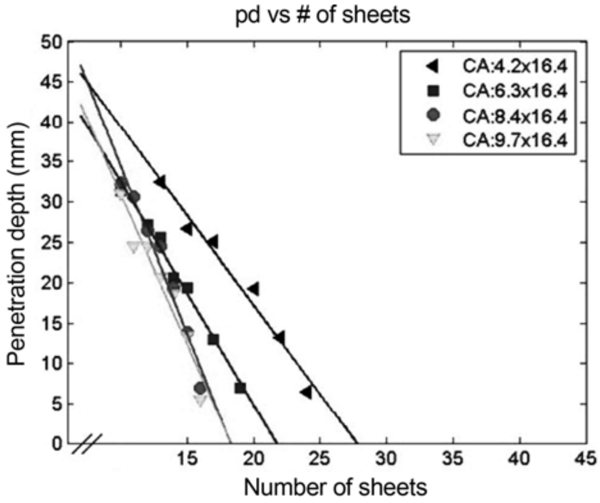

Figure 8. Penetration depths of the aramid hybrid textile structures relative to the number of fabric sheets.

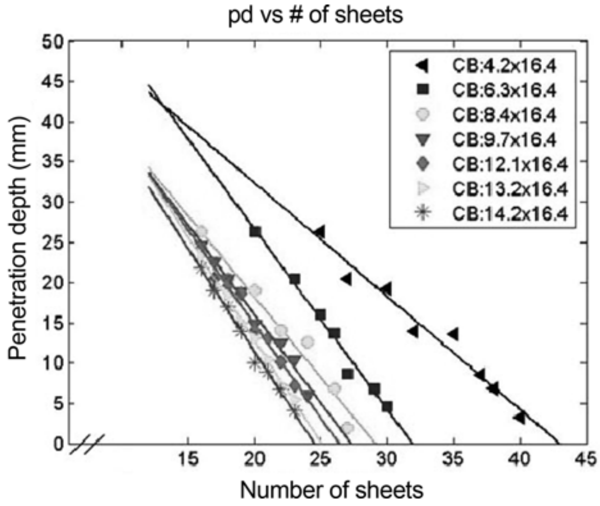

Figure 9. Penetration depths of the basalt hybrid textile structures relative to the number of fabric sheets.

Aramid Textiles

The penetration depth was measured according to the number of the specimen layers for various aramid hybrid fabrics (Figure 8). In nature, depth decreases with more specimen layers. As seen in Figure 8, this relationship was illustrated, with the penetration depth decreasing, as the number of specimen layers increased, which indicates that the thicker the specimen is, the greater is the resistance against penetration.

These results are influenced by the fabric density; a larger fabric density led to a steep decrease in penetration depth. However, the influence of fabric density weakens in high density fabrics. The specimens with fabric densities of 8.4×16.4 and 9.7×16.4 had almost identical penetration depths, indicating that the fabric condition 9.7×16.4 does not improve the penetration depth. Having a weft density greater than 8.4 picks/cm does not appear to improve anti-stabbing performance for aramid-based hybrid armor fabrics. Thus, there seems to be an optimal fabric density level for stab resistance: in the case of aramid hybrid fabrics, it was 8.4×16.4.

Basalt Textiles

The stabbing test results for the basalt hybrid textile structures are given in Figure 9.

The penetration depth with respect to the number of sheets can be interpreted in the same manner as the aramid textile structure. Thus, the greater was the number of layers, the smaller was the penetration depth. Fabric density also had an influence on penetration depth, with an efficient fabric density level being approximately 9.7×16.4 (weft yarns/cm×warp yarns/cm).

Metallic Textiles

The penetration depth of the specimens, composed of metal hybrid yarns according to the number of specimen layers is given in Figure 10.

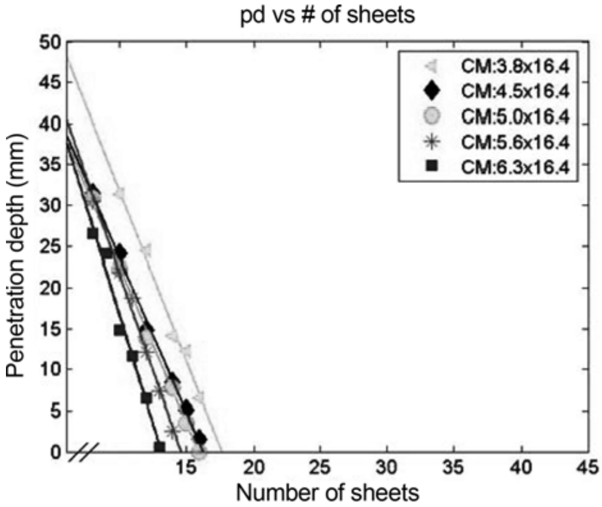

Figure 10. Penetration depths of the metal hybrid textile structures relative to the number of fabric sheets.

As seen in the results from the previous measurements, the penetration depth decreased in a linear form approximately, as the number of specimen layers increased. The higher was the fabric density, the better was the stab resistance. However, effective fabric conditions are not necessarily apparent under experimental circumstances.

All of the aforementioned results, however, could be interpreted in terms of the sample thickness or mass.

Effect of Specimen Thickness

The thickness of one layer of armor fabric can be different from the others, if the fabric conditions or the materials change. Armor thickness is an important factor in comfortable wearability. Therefore, the penetration depth behaviors of armor specimens were analyzed in terms of specimen thickness.

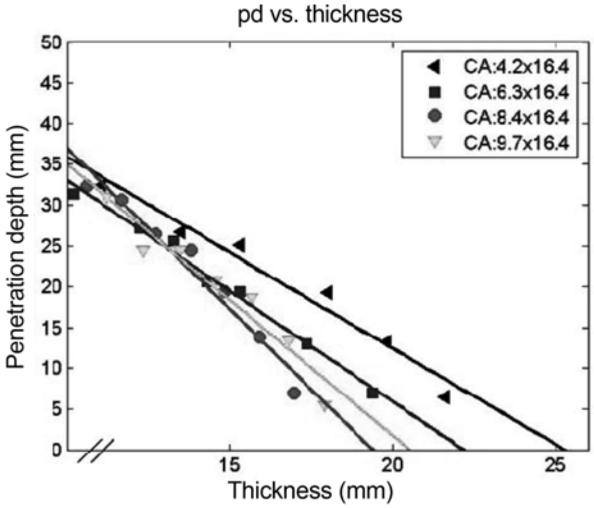

Figure 11. Penetration depths of the aramid textile structures relative to sheet thickness.

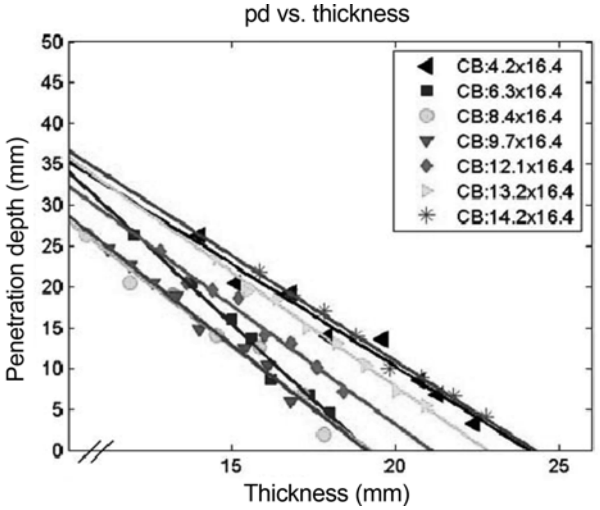

Figure 12. Penetration depths of the basalt hybrid textile structures relative to sheet thickness.

Aramid Textiles

The penetration behaviors of the aramid hybrid fabrics against the S1 knife stabbing were analyzed with respect to specimen thickness (Figure 11).

As the specimen thickness increased, the penetration depth decreased. However, the decreasing penetration depth was influenced by fabric density. A higher fabric density led to reduced penetration; thus, any change in the thickness of the armor fabric affects the depth penetrated by the stabbing knife. Armor fabrics with higher fabric densities are more sensitive to stabbing impacts according to fabric thickness than are those with lower fabric densities, indicating that low density fabrics must be thicker than higher density fabrics to achieve the same penetration depth.

Basalt Textiles

Basalt specimens also have similar anti-stabbing behaviors due the thickness; as thickness increases, the penetration depth decreases (Figure 12). However, the steepness of the line approximating the penetration depth-thickness relationship showed no significant difference for fabric densities, whereas the fabric density revealed the optimum condition for the fabric density to be located between 8.4 (picks/cm)×16.4 (ends/cm) and 9.7 (picks/cm)×16.4 (ends/cm). An extremely low fabric density or an extremely high fabric density, however, resulted in poor anti-stabbing resistance. Thus, penetration depth behavior might be closely related to the tensile and tearing strengths of the fabric specimens, which have not yet been identified.

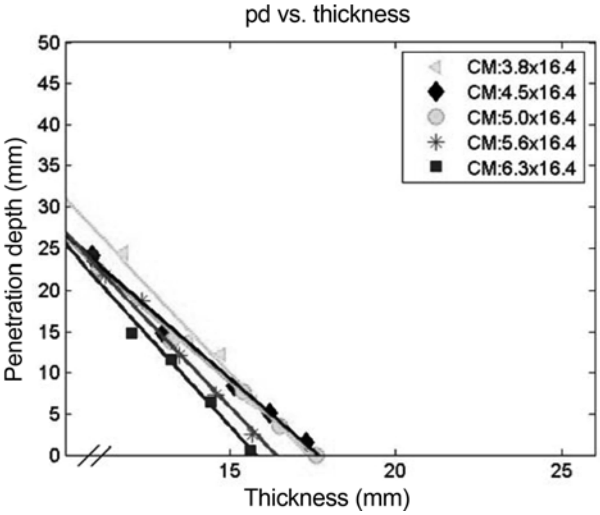

Figure 13. Penetration depths of the metal textile structures relative to sheet thickness.

Metallic Textiles

The stabbing resistance behaviors of the armor fabrics containing metal fibers are given in Figure 13.

As with previous specimens, penetration depth decreased with increasing specimen thickness. The influence of fabric density on the penetration depth was observed such that high fabric density led to a lower penetration depth.

Effect of Specimen Weight

Body armor should protect the human body against emergent accidents or external attacks; therefore, the weight of the armor fabric is a very important factor in terms of body protection performance. We examined the effects of specimen weight on stabbing resistance, also considering the penetration depth of the impactor according to the areal densities of the specimens for various materials.

Aramid Textiles

Aramid fiber is a well-known material with a high strength per weight, inferring good protection against anti-stabbing objects. Figure 14 shows the test results of the penetration depth with respect to areal density for the aramid hybrid armor fabrics.

As expected, the increase in specimen weight led to a

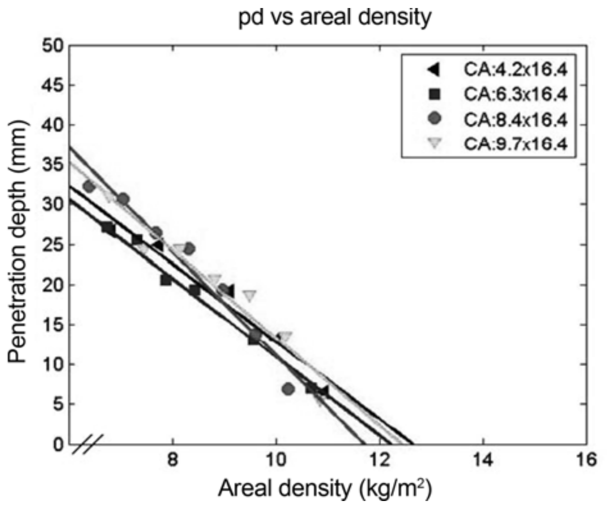

Figure 14. Penetration depths of the aramid textile structures relative to the areal density of fabric sheets.

decrease in penetration depth. However, it appears that fabric density produces no significant difference in stabbing resistance.

Basalt Textiles

The penetration depths of the basalt hybrid fabrics with respect to areal density are shown in Figure 15. The weights of the basalt hybrid armor fabrics had large effects on the penetration depth. Even though a higher areal density produced to a lower penetration depth, the fabric density showed an optimal value range between 6.3×16.4 (picks/cm) and 9.7×16.4 (ends/cm). An extremely high or low fabric density led to low anti-stabbing performance, that is, a deeper penetration.

Metallic Textiles

Figure 16 illustrates the stabbing test results for the metal hybrid armor fabrics. Higher specimen weights led to decreases in penetration depth. However, fabric density had no significant influence on stabbing resistance under the experimental conditions.

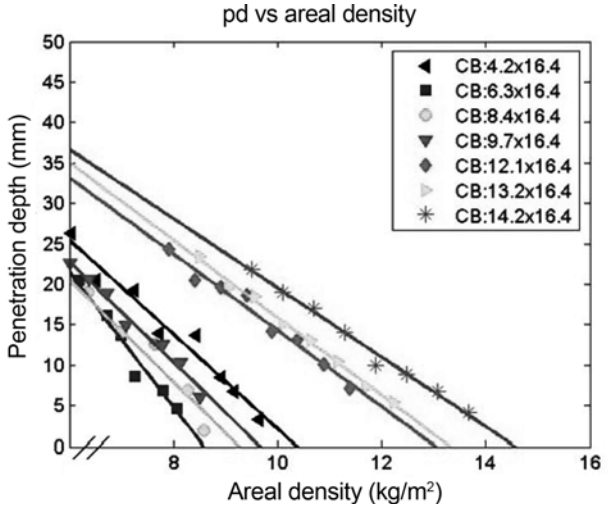

Figure 15. Penetration depths of the basalt hybrid textile structures relative to the areal density of fabric sheets.

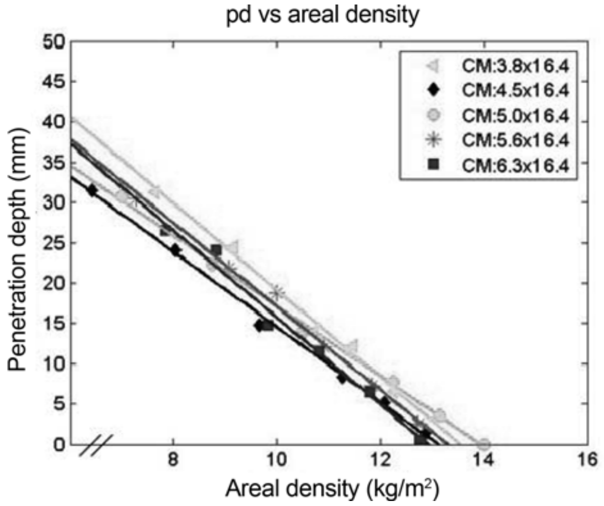

Figure 16. Penetration depths of the metal hybrid textile structures relative to the areal density of fabric sheets.

Anti-stabbing Index

In the tests, penetration depth was used as the measured value; however, specimen performance against stabbing cannot be interpreted consistently, because factors such as thickness and weight have different influences on the penetration depth. To provide a criterion capable of predicting or determining anti-stabbing performance, an index which takes these factors into account is helpful. Since penetration depth showed decreasing tendencies for areal density and specimen thickness, and the penetration depth required to protect the human body against a stabbing threat is assigned by the NIJ standard as 7 mm, our anti-stabbing index was defined as:

$$ASI = (TH_{standard\,penetration\,depth}) \cdot (AD_{standard\,penetration\,depth})$$

where $TH_{standard\,penetration\,depth}$ and $AD_{standard\,penetration\,depth}$ are thickness and areal density of the armor specimen required for the standard penetration depth respectively.

We obtained results that showed the best anti-stabbing indices for each material (Table 4). The basalt specimens revealed the best anti-stabbing performance for fabric conditions of 6.3 (picks/cm)×16.4 (ends/cm), with 29 sheets and an ASI value of 133.21. Aramid hybrid armor fabrics,

Table 4. Anti-stabbing indices (ASI) for the best armor fabrics

Material	Fabric density (ppc.×epc.)	Number of sheets	Thickness (mm)	Areal density (kg/m²)	ASI
Basalt	6.3×16.4	29	17.3	7.7	133.21
Aramid	8.4×16.4	17	17.6	10.6	186.56
Metal	6.3×16.4	12	14.2	11.6	164.72

on the other hand, showed the best anti-stabbing performance for fabric conditions of 8.4 (picks/cm)×16.4 (ends/cm), with 17 sheets and an ASI value of 186.56. The metal hybrid fabrics had the best anti-stabbing performance under fabric conditions of 6.3 (picks/cm)×16.4 (picks/cm). This specimen consisted of 12 sheets, showing an ASI value of 164.72. Since a smaller ASI value indicates a superior anti-stabbing performance, these experimental results imply that the basalt hybrid armor fabrics had the best anti-stabbing performance, while the aramid hybrid specimens were the worst.

These results, however, do not indicates that the aramid fabrics are inferior to the basalt fabrics in terms of anti-stabbing performance. In a different range of the fabric densities and for raw materials with different specifications, the results could differ. Thus, we refrain from making any general comments on the superiority of specific materials until all possible test results have been collected. Thus far, it is sufficient to compare different conditions and materials in order to evaluate the best anti-stabbing performance based on the anti-stabbing indices suggested in this research.

Conclusion

In order to protect the human body against stabbing threat, anti-stabbing performance was tested, using a tower drop method in accordance with the NIJ standard. The armor specimens were prepared in the form of woven fabrics of hybrid type special yarns, in which aramid, basalt, and metal fibers were used with a combination of cotton fibers to improve wear comfort.

Our results showed that the changes in fabric density strongly affected the stab resistance. The penetration depth of the impactor was influenced by the number of layers, the thickness, and the mass of the armor sample. We confirmed that an optimal fabric density level, in terms of being the most stab resistant, does exist.

We also derived an anti-stabbing index that can be used as a criterion for comparing the anti-stabbing performances of various armor specimens composed of different fabric conditions and materials. According to the ASI, the basalt hybrid fabrics showed the best anti-stabbing performance compared to those of the other specimens.

Acknowledgement

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